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Design and modeling of surface acoustic wave sensor with staggered ID – tag

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Abstract

A design methodology of wireless surface acoustic wave (SAW) sensor with staggered ID – tag is presented. For longer reading distances and technology improvement unidirectional transducers, working on the main frequency harmonics, are proposed. To reduce the number of strips and the size of devices is offered to increase the reflection coefficient and use open circuit reflectors. Unique technological realizations of SAW reflecting elements and unidirectional transducers, that enable to increase reflection coefficient and unidirectionality are proposed. A model of wireless sensor based on transfer matrixes of equivalent circuits of the device elements is created. The model discloses interaction among separate elements, assessed charge distribution in electrode's type, secondary effects, losses, wave's speed change constituents and allows to analyze characteristics and parameters of SAW sensors that have various structures. Simulation results are presented.

Keywords: Surface acoustic wave, sensor, identification tag, unidirectional SAW transducer, metal strip reflectors, parallel acoustic channel, modeling.

Introduction

The characteristics of surface acoustic wave (SAW) devices make them well suitable for the application of wireless sensors or wireless identification tags. They are small, robust and operate completely passive. Integrated circuit technology allows the sensors to produce in large quantities, thus obtaining a low production cost. The sensor itself uses the energy from the transmitted pulse and operates without any external power supply, which makes it a good choice for long term applications under difficult conditions such as subsurface sensing or measurements on rotating parts [1]. Reprogrammable and powerful data processing devices together with fast and reliable networks opens a huge number of totally new possibilities on a field of radar technology [2, 3]. In the known wireless SAW sensors external influence is determined through SAW device impulse response changes. The sensing mechanism is based on a variation of the SAW velocity in the substrate. Variation of the SAW velocity is in relationship also by temperature dependent delays. With simple sensor concepts, it is nearly impossible to separate these two influences in the interrogation unit. A recent type of two–port SAW radio transponders avoid the direct effect to the piezoelectric substrate but employ electrically loaded interdigital transducer (IDT) [4]. Therefore, the sensitivities for other effects to the sensor can be minimized by suitable packaging and proper selection of external sensible elements. This is also suitable for another remote reading SAW sensors such as identity tags, wireless pressure sensors, wireless gas sensors, strain sensors, hospital sterilizer etc. The sensors withstand a high rate of radiation and a powerful electromagnetic interference up to the power endurance of the device. A damage occurs if the electric field strength within the IDT exceeds the breakthrough threshold between the IDT fingers. For 433 MHz devices, this upper limit is at a few volts rms [5]. When using IDT type transducer as a sensible element it is possible to evaluate the thickness of the granule flow [6].

In this paper a design methodology of SAW transponder sensor with staggered identification (ID) tag, external sensible element of which is connected to an output interdigital transducer of surface acoustic wave delay line, is proposed.

Design of SAW transponder sensor

The simplest SAW transponder sensor is shown in Fig. 1. It is representing a SAW delay line on the piezoelectric substrate, containing two IDTs. One is connected to the antenna (IDT1), and the second (IDT2) is electrically loaded by external impedance Z_L, whose value depends on the measured parameter. The external sensor, which varies its impedance in dependence of the sensing quantity, influences the reflectance by this second IDT and, therefore, modifies the phase and amplitude of the reflected wave.

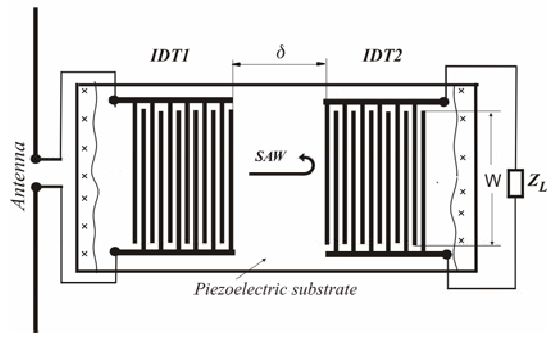

Fig. 1. **SAW transponder sensor**

The Impulse Response method was used to model the SAW delay line [7]. It uses the Mason equivalent circuit shown in Fig. 2. For each IDT, the model is comprised of the radiation conductance G_a, the acoustic susceptance B_a, and the IDT static capacitance C_T. This is a first order model only. However, it does model the piezoelectric, mechanical and electrical behaviors of the SAW device.

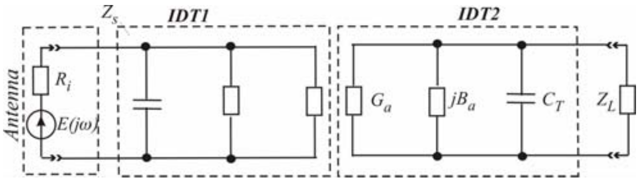

Fig. 2. **The equivalent circuit of the SAW transponder sensor**

Reflectance is a complex parameter expressed by the simplified formula:

$$\Gamma_a = \frac{G_a}{G_a + j(\omega C_T + B_a) + 1/Z_L}, \tag{1}$$

where $\omega = 2\pi f$; f is the operating frequency.

The dependencies of G_a and B_a on the frequency f are given by [7]:

$$G_a = 8k_m^2 f_0 C_T N \left(\frac{\sin X}{X}\right)^2; \tag{2}$$

$$B_a = 8k_m^2 f_0 C_T N \left(\frac{\sin 2X - 2X}{2X^2}\right), \tag{3}$$

where $X = \pi N(f - f_0)/f_0$; k_m^2 is the electromechanical coupling coefficient; f_0 is the transducer center frequency; N is the number of transducer fingers.

The capacitance of the overlapping transducer fingers is calculated in the following way:

$$C_T = C_0 NW, \tag{4}$$

where W is the IDT aperture; C_0 is the capacitance per unit finger length.

C_0 will be expressed as the simplified formula:

$$C_0 = \frac{1}{2}(\varepsilon_0 + \varepsilon_p^T)\,K\left[\sin\left(\frac{1}{2}\pi\eta\right)\right] \Big/ K\left[\cos\left(\frac{1}{2}\pi\eta\right)\right], \tag{5}$$

where ε_0 is the free–space dielectric permittivity; ε_p^T is the dielectric permittivity of piezoelectric substrate at constant mechanical tension; K is the complete elliptic integral of the first kind; η is the metallization ratio.

Unlike SAW ID tag, the SAW transponder sensor IDT acoustic reflectance Γ_a must be calculated more precisely. Accurate reflection coefficient values can be obtained from the equivalent circuit's model, which assessed charge distribution in electrodes type, secondary effects, losses and waves speed change constituents. In this case, the reflection coefficient can be expressed as:

$$\Gamma_a = \frac{z_0 - z_T}{z_0 + z_T}, \tag{6}$$

where z_0 is the acoustic impedance of piezoelectric substrate.

The acoustic impedance of the transducer z_T can be calculated by the formula:

$$z_T = \frac{a_{11}^T Z_L + a_{12}^T}{a_{21}^T Z_L + a_{22}^T}, \tag{7}$$

where a_{ij}^T is the electrically loaded by an external impedance Z_L the transducer transfer matrix element.

As the reflection characteristic is determined by the transducer, we shall describe models of the transducer exciting SAW within electrodes and the models of transducers in general, in which we shall evaluate SAW velocity variations, loss components and non uniform electrical charge distribution within electrodes.

Processes that take place in piezoelectrics are described by the Maxwell electrodynamic, acoustic and piezoeffect equations under a condition of quasi electrostatic approximation. Coupling between electrical and mechanical quantities is fully defined by the wave equation system for electrical potential and three elastic shift projections. Solving these equations under a condition that the elastic body is quasi isotropic, the vector of energy flow coincides with the vector of wave propagation direction, the elastic medium is quasi linear and the coefficient of electromechanical coupling – poor, it has been proving that frequency response depends only on a charge distribution within electrodes. Therefore, while creating the transducer model it is enough to describe any of elastic displacement directions of piezoelectric particles and is possible to consider the acoustic wave not coupled to an electrical field. Then the problem is divided into the problems of electrostatics and acoustic wave excitation.

The equation system describing particle velocities ξ_1, ξ_2 of the force F_1, F_2 at the edges of SAW transducer electrodes will be expressed as follows [8]:

$$\begin{cases} F_2 + F' = (F_1 + F')\operatorname{ch}\gamma_e l_e + z_e(\xi_1 - \xi')\operatorname{sh}\gamma_e l_e; \\ \xi_2 - \xi' = \dfrac{1}{z_e}(F_1 + F')\operatorname{sh}\gamma_e l_e + (\xi_1 - \xi')\operatorname{ch}\gamma_e l_e, \end{cases} \tag{8}$$

where $F' = s_0 U$; $\xi' = \dfrac{r_0}{z_e}U$; s_0, r_0 are the coefficients of electromechanical transformation and gyrator; z_e is the acoustic impedance under the electrode; γ_e is the propagation constant; l_e is the electrode width.

Relying to Eq. 8 and [8], the transducer electrode transmission matrix will be as follows:

$$\left[A^E\right] = \begin{bmatrix} a_{11}^E & a_{12}^E & a_{13}^E & 0 \\ a_{21}^E & a_{22}^E & a_{23}^E & 0 \\ 0 & 0 & 1 & 0 \\ a_{41}^E & a_{42}^E & a_{43}^E & 1 \end{bmatrix}, \tag{9}$$

where

$$a_{11}^E = \operatorname{ch}\gamma_e l_e\,;\; a_{12}^E = z_e \operatorname{sh}\gamma_e l_e\,;$$

$$a_{13}^E = s_0(\operatorname{ch}\gamma_e l_e - 1) - r_0 \operatorname{sh}\gamma_e l_e\,;$$

$$a_{21}^{E}=\frac{1}{z_e}\text{sh}\gamma_e l_e\,;\;a_{22}^{E}=\text{ch}\gamma_e l_e\,;$$

$$a_{23}^{E}=\frac{1}{z_e}\left[s_0\text{sh}\gamma_e l_e-r_0\left(\text{ch}\gamma_e l_e-1\right)\right];$$

$$a_{41}^{E}=\frac{1}{z_e}\left[s_0\text{sh}\gamma_e l_e+r_0\left(\text{ch}\gamma_e l_e-1\right)\right];$$

$$a_{42}^{E}=s_0\left(\text{ch}\gamma_e l_e-1\right)+r_0\text{sh}\gamma_e l_e\,;$$

$$a_{43}^{E}=\frac{1}{z_e}\left(s_0^2-r_0^2\right)\text{sh}\gamma_e l_e+j\omega C_0\,.$$

Then the transducer transmission matrix will be the following:

$$\left[A^T\right]=\left[A^R\right]\cdot\left[A^{BW}\right]\cdot\left(\prod_{n=1}^{N-1}\left[A^B\right]_n\left[A^E\right]_n\left[A^B\right]_n\left[A^L\right]_n\right)\times\times\left[A^B\right]_N\left[A^E\right]_N\left[A^B\right]_N,\qquad(10)$$

where $[A^L]$ is the transfer matrix of the equivalent circuit that describes gaps between neighboring electrodes; $[A^R]$, $[A^{BW}]$ – transfer matrixes evaluating ohmic losses within transducer electrodes and losses on the bulk–wave generation respectively; $[A^B]$ – reactive conductivity of the reactive energy accumulation at the electrode edges (acoustic discontinuity) transfer matrix.

Then the electrically loaded transducer transfer matrix elements a_{ij}^T are calculated as:

$$a_{11}^T=A_{13}^T+\frac{A_{43}^T(A_{12}^T+A_{11}^T z_0)}{A_{42}^T+A_{41}^T z_0};\quad a_{12}^T=-\frac{A_{12}^T+A_{11}^T z_0}{A_{42}^T+A_{41}^T z_0};$$

$$a_{21}^T=A_{23}^T+\frac{A_{43}^T(A_{22}^T+A_{21}^T z_0)}{A_{42}^T+A_{41}^T z_0};\quad a_{22}^T=-\frac{A_{22}^T+A_{21}^T z_0}{A_{42}^T+A_{41}^T z_0},$$

where A_{ij}^T is the transducer transfer matrix $[A^T]$ elements.

In order to achieve the maximum capability of the sensor dynamics, load must be series – resonant circuit [4], but, as shown by calculations, simple electrode transducer reflectivity is strongly influenced by capacity. Maximum acoustic reflection is obtained when the load capacity is in the range of the transducer capacity. Fig. 3 shows the acoustic reflection coefficient dependence from the load capacitance C_L, where the number of strips $N=15$, operating frequency $f_0=433$ MHz, piezoelectric substrate – YZ $LiNbO_3$.

The low insertion losses are important to SAW transponder sensor. Traditional transducers are two – directional. Therefore, there are formed losses. The mentioned shortcoming may be lessened with the help of unidirectional transducers. To increase unidirectionallity in transducer structures is possible using acoustic non– uniformities of various types, among them and in allowed ranges. In the transducer are used split electrodes, parts of which are of different thickness. Having excited the transducer, the wave propagates in both directions. From a split electrode the wave reflects.

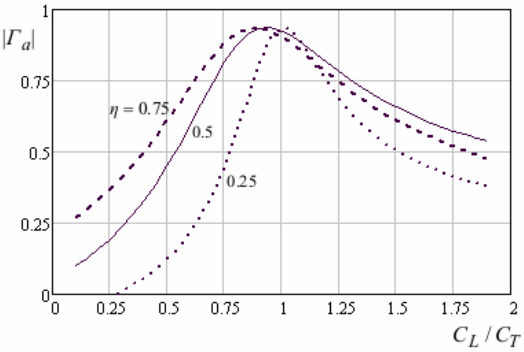

Fig. 3. **The acoustic reflection coefficient dependence from the load capacitance**

Reflection from the thicker electrodes cophasally sums up with the wave that propagates in a forward direction, and with reversed opposite phase – in a symmetrically equal direction. As the width of split electrodes equals to $\lambda_0/8$, here λ_0 is the SAW length, and the distance between the doubled electrodes centers are $\lambda_0/4$, the SAW propagates in the main direction. Analogically waves are reflected from thinner electrodes. The reflection coefficient of thinner electrodes is smaller. Therefore, the wave propagating in a forward direction partially attenuates the wave reflected from the electrodes. To decrease this attenuation, it is necessary to make acoustic impedances uniform. For this purpose the piezoelectric material, which is under the thinner electrode is alloyed by ions.

In the other construction of a unidirectional transducer, in which there was used ion implantation, under the part of electrodes is the dielectric underlayer, and under it – the ion alloyed waveguide surface. The acoustic impedance of the the alloyed layer is smaller than the impedance of piezoelectric free surface. Mismatch of acoustic impedances of the electrode part with a dielectric underlayer is bigger than the electrode part, that is directly on the piezoelectric surface. If the width of a dielectric underlayer approximately is equal to $\lambda_0/4$, so waves reflected in one direction sum up cophasally and in the other direction – by reversed phases. Because of acoustic nonuniformities the reflected SAW energy increases, and the transducer unidirectionality grows for 7 – 12 decibels. To increase unidirectionality of transducers with isolated electrodes, there are used ravines or ion alloyed acoustic non-uniformities. The width of the isolated electrode and acoustic non – uniformity makes up $0{,}15\lambda_0$ and $0{,}2\lambda_0$. The propagating SAW reflects from the edges of isolated electrodes, the impedance of which is smaller than the impedance of piezoelectric free surface. As isolated electrodes are laid asymmetrically with respect to the exciting electrodes, the waves sum up cophasally. Acoustic non – uniformities the impedance of which is bigger than the impedance of piezoelectric free surface, for 6 – 10 decibels increase unidirectionality of the transducer.

To make sensors with the identification ability at the same time, tags should have programmable reflectors. Reflectors are used as bits of the serial response data word with a pulse amplitude modulation, a pulse position modulation or a pulse phase modulation. There are two methods signals coding. One is the usage of a different number of strips in different reflectors, another one is adoptions of different aperture among different channel. For tags with channel in the same line there is reflector loss and multiple echoes caused by SAW passing through the reflectors. Tags with staggered reflectors have no multiple echoes among reflectors, the noise level is lower than that of the tag with channel in the same line. To reduce losses, a parallel cannel can be used.

Reflecting grating of SAW ID sensors are made of acoustic nonuniformities. To reduce the number of strips, it is necessary to increase the reflection coefficient of the latter. For this purpose, ion implantation was used. For different acoustic impedances of free and metallized surfaces of piezoelectric, part of the SAW energy reflects from the edges of metal strips, sums up cophasally and they form the reflected wave. Gaps between metal strips are dopes by ions of light chemical elements. Therefore, in these ranges the acoustic impedance as well as the reflection from the metal strip edges coefficient increase significantly. For example, having implanted helium ions, the energy of which are 125 keV and the dose – $1{,}5\text{x}10^{20}$, the coefficient of the SAW reflection from one strip increases to 0,166 instead of 0,095, YX cut for quartz or to 0,126 instead of 0,065 ST, X cut for quartz.

In SAW tag design procedure, reflectors at various locations in a device would be designed with varying reflectivity to compensate for the energy loss of preceding reflectors so that they could have uniform amplitudes of reflected pulses. This requirement can be implemented by changing the metallization ratio. The structure of distributed reflectors located on two sides of a bidirectional IDT and in a straight line cannot be used as sensors based upon ID – tags, because of its multiple reflections among reflectors on both sides of the IDT. To get the correct signal of sensor, unlike tags used as identification, passive sensor should have not a large number of reflectors. We should make the insertion losses as low as possible when the least number of bits is satisfied, because the more bits, the higher the insertion loss.

To obtain the reflection coefficient for the short – circuited and open circuit reflectors also equivalent circuit method can be used. The metall strip transfer matrixes for the short – circuited (SC) and open circuit (OC) reflectors are given by respectively [8]:

$$\left[A_G^U\right]=\begin{bmatrix}\mathrm{ch}\gamma_u l_e & z_u \mathrm{sh}\gamma_u l_e\\ \dfrac{1}{z_u}\mathrm{sh}\gamma_u l_e & \mathrm{ch}\gamma_u l_e\end{bmatrix}; \qquad (11)$$

$$\left[A_G^L\right]=\begin{bmatrix}\mathrm{ch}\gamma_e l_e + a & z_e \mathrm{sh}\gamma_e l_e - b\\ \dfrac{1}{z_e}\mathrm{sh}\gamma_e l_e - c & \mathrm{ch}\gamma_e l_e + a\end{bmatrix}, \qquad (12)$$

where

$$a=\frac{\mathrm{sh}\gamma_e l_e\left(1-\mathrm{ch}\gamma_e l_e\right)}{\mathrm{sh}\gamma_e l_e + j\dfrac{\omega l_e}{k_m^2 v_e}};$$

$$b=\frac{z_e\left(1-\mathrm{ch}\gamma_e l_e\right)}{\mathrm{sh}\gamma_e l_e + j\dfrac{\omega l_e}{k_m^2 v_e}};\quad c=\frac{\dfrac{1}{z_e}\mathrm{sh}^2\gamma_e l_e}{\mathrm{sh}\gamma_e l_e + j\dfrac{\omega l_e}{k_m^2 v_e}};$$

z_u , γ_u are the strip impedance and the SAW propagation constant for the short – circuited reflectors respectively, v_e is the acoustic wave propagation speeds under strip.

Fig. 4 shows the acoustic reflection coefficient Γ_a dependence for the SC and OC reflectors, from the metalization ratio η, where the number of strips N_{ref} = 9, the aluminum metallization thickness 0,2 µm, the operating frequency $f_0 = 433$ MHz, the piezoelectric substrate is YZ $LiNbO_3$.

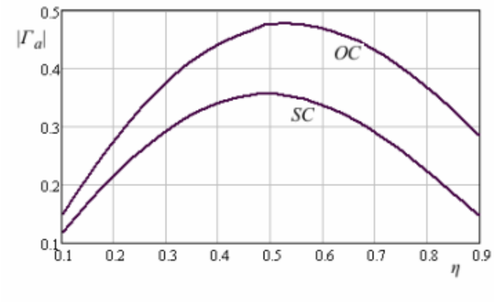

Fig. 4. **The acoustic reflection coefficient dependence for the short - circuited (SC) and open circuit (OC) reflectors**

As shown in Fig. 4, OC reflector has a greater acoustic reflection coefficient at the same number of strips. Therefore, it is better suited for the sensor design. Design process must determine the right number of strips in the reflector that not significantly suppress the sensor transducer response. Coming to the antenna power among all the parallel channels of the reflectors and the sensor, the transducer is to be shared equally. To minimize size and to satisfy this condition, it is necessary to choose the minimum number of strips in the reflectors at which the sum of all responses from the SC reflectors is equal to the sensor transducer maximum response $|h|_{\max}$. From the calculations (Fig. 5) we find that this condition is satisfied when $N_{ref} = 9$, $\eta = 0{,}5$.

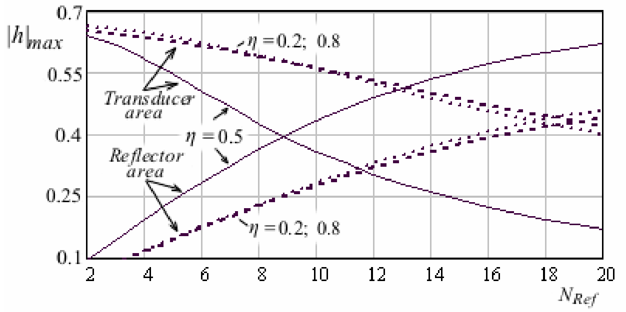

Fig. 5. **The maximum response of the reflected signal on the antenna connector dependence from the reflector strip number**.

Evaluation of surface acoustic wave sensor with staggered ID – tag

After analysis, the proposed SAW transponder sensor was realized by the multi–channel delay line (Fig. 6). Exciting and sensor transducer is placed on the surface of YZ LiNbO3 substrate. Reflectors are placed in parallel channels between the transducers. Reflection of the sensor transducer is modulated by an external impedance Z_L. Other fixed reflectors are used as reference bits. ID is formed by different time – delay acoustic reflections from the reflectors.

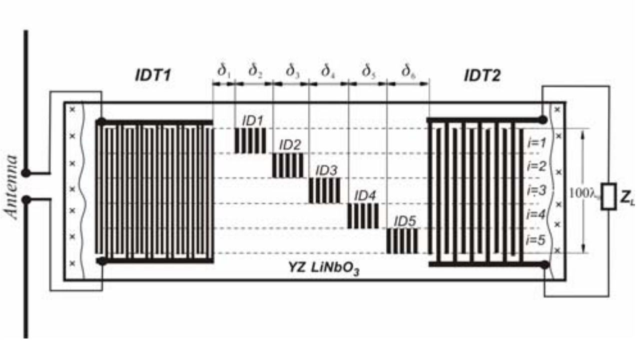

Fig. 6. **The wireless SAW sensor with staggered ID – tag**

This type of sensor can be modeling by dividing into separate parallel channels [8]. The number of channels is the same as the reflector number. Channel electric and acoustic elements describe the transfer matrix. Each channel electrical terminals are connected in parallel. The sensor channel transfer matrix is obtained by multiplying the transfer matrices of its electric and acoustic elements. If the structure consists of M – channels, then the i – channel transfer matrix is:

$$[A^S]_i = [A^{T1}]_i[A^{T1R}]_i[A^{ID}]_i[A^{RT2}]_i[A^{T2}]_i\,, \qquad (13)$$

where $[A^{T1}]_i$, $[A^{T2}]_i$ is the exciting and the sensor transducer transfer matrixes; $[A^{T1R}]_i$, $[A^{RT2}]_i$ is the transfer matrixes of substrate gaps, evaluating the SAW losses of piezoelectric viscosity, air loads, diffraction. $[A^{ID}]_i$ is the transfer matrix of reflector.

Since the separate channels electrical terminals are connected in parallel, the transfer matrix $[A^S]_i$ is replaced by the conductivity matrix $[Y^S]_i$ [8]:

$$[Y^S]_i = \begin{bmatrix} \dfrac{a_{12}^{S_i}}{a_{12}^{S_i}} & -\dfrac{\left|a^{S_i}\right|}{a_{12}^{S_i}} \\ \dfrac{1}{a_{12}^{S_i}} & -\dfrac{a_{11}^{S_i}}{a_{12}^{S_i}} \end{bmatrix}, \qquad (14)$$

where $a_{ij}^{S_i}$ is the transfer matrix $[A^S]_i$ elements; $\left|a^{S_i}\right| = a_{11}^{S_i}a_{22}^{S_i} - a_{21}^{S_i}a_{12}^{S_i}$ is the matrix determinant.

The total conductivity matrix can be written:

$$[Y^S] = \sum_{i=1}^{M}[Y^S]_i \qquad (15)$$

and the total transfer matrix will be expressed as follows:

$$[A^S] = \begin{bmatrix} \dfrac{y_{22}^S}{y_{21}^K} & \dfrac{1}{y_{21}^S} \\ \dfrac{|y_S|}{y_{21}^S} & \dfrac{y_{11}^S}{y_{21}^S} \end{bmatrix}, \qquad (16)$$

where $\left|y^S\right| = y_{11}^S y_{22}^S - y_{21}^S y_{12}^S$.

The responses of the sensor are obtained in the time domain. For an antena (Fig. 2), the impulse response can be calculated by inverse discrete Fourier transform:

$$h(t) = \frac{U_{ref}(t)}{E_0} = \frac{R_i}{2\pi\cdot E_0}\int_{-\infty}^{\infty}\frac{E(j\omega)}{R_i + Z_S(j\omega)}\cdot e^{j\omega t}d\omega, \quad (17)$$

where

$$E(j\omega) = \int_{-\frac{\tau}{2}}^{\frac{\tau}{2}} E_0\cos\omega_0 t\cdot e^{j\omega t}dt; \qquad (18)$$

$$Z_S(j\omega) = \frac{a_{11}^S R_i + a_{12}^S}{a_{21}^S R_i + a_{22}^S}; \qquad (19)$$

$U_{ref}(t)$ is the reflected voltage; E_0 is the antenna pulse amplitude; τ is the pulse duration; a_{ij}^S is the transfer matrix $[A^S]$ elements.

Fig. 7 shows the reflection characteristics of the wireless SAW sensor with staggered ID – tag. The pulse duration is 14 ns, operating frequency – 433 MHz. The number of strips (Fig. 6): IDT1, IDT2 – 15, ID reflectors – 9; $\delta_1 = 90\lambda_0$, $\delta_2 = \delta_3 = \delta_4 = \delta_5 = 30\lambda_0$, $\delta_6 = 70\lambda_0$. In the unidirectional transducer IDT1 are used split electrodes, parts of which are of a different thickness.

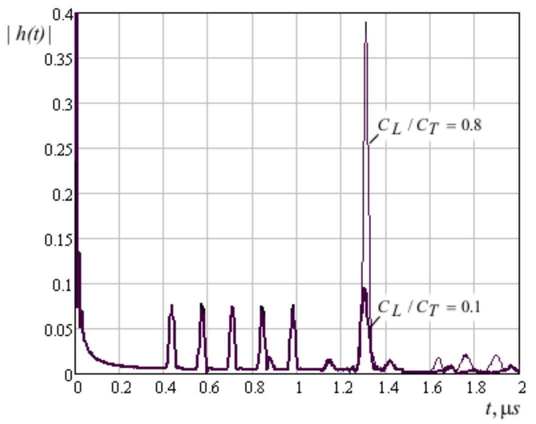

Fig. 7. **The reflection characteristics of the wireless SAW sensor with staggered ID – tag.**

Conclusions

In this work the design methodology of wireless SAW sensor with staggered ID tag, external sensible element of which is connected to an output interdigital transducer of surface acoustic wave delay line is proposed. After analysis, the proposed SAW transponder sensor, was realized by the multi – channel delay line with a staggered ID tag, which has no multiple echoes between reflectors. For longer reading distances and technology improvement unidirectional transducers, working on the main frequency harmonics are proposed. To lessen the size of devices and the number of strips it is necessary to increase the reflection coefficient and use open circuit reflectors. There are offered unique technological realizations of SAW reflecting elements and unidirectional transducers, that enable to increase reflection coefficient and unidirectionality. In this work a model of wireless sensor, based on transfer matrixes of equivalent circuits of the device elements is created. The model discloses interaction among separate elements, assessed charge distribution in electrode's type, secondary effects, loss, wave's speed change constituents and allows to analyze characteristics and parameters of devices that have various structures.

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A. Janeliauskas

Paviršinių akustinių bangų jutiklio su išskirstytuoju atpažinimo žymeniu projektavimas ir modeliavimas

Reziumė

Pasiūlyta bevielio paviršinių akustinių bangų (PAB) jutiklio su išskirstytuoju atpažinimo žymeniu projektavimo metodika. Didesniam skaitymo nuotoliui ir jutiklio technologiškumui užtikrinti siūloma naudoti vienkrypčius keitiklius, dirbančius pagrindinio dažnio harmonikose. Norint sumažinti elektrodų skaičių ir įtaiso matmenis, reikia naudoti laisvųjų elektrodų atspindinčius reflektorius ir padidinti atspindžio koeficientą. Pasiūlyti PAB atspindžio elementų ir vienkrypčių keitiklių technologiniai sprendimai, leidžiantys padidinti atspindžio koeficientą ir vienkryptiškumą. Sukurtas bevielio jutiklio modelis, aprašantis įtaiso elementus ekvivalentinėmis schemomis ir jų perdavimo matricomis. Modelis įvertina tam tikrų elementų sąveiką, krūvio pasiskirstymo elektroduose pobūdį, antrinius efektus, nuostolių ir bangos greičio pokyčio dedamąsias ir leidžia analizuoti įvairių struktūrų PAB jutiklių charakteristikas ir parametrus. Pateikti modeliavimo rezultatai.

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