**Milan ŠIMKO[1], Milan ŠEBOK[1], Milan CHUPÁČ[1], Daniel KORENČIAK[1], Miroslav GUTTEN[1]
Katarzyna PIOTROWSKA[2], Pawel ZUKOWSKI[3], Tomasz N. KOLTUNOWICZ[3]**

University of Zilina, Zilina, Slovakia (1), Institute of Technological Systems of Information, Lublin University of Technology, Lublin, Poland (2), Department of Electrical Devices and High Voltage Technologies, Lublin University of Technology, Lublin, Poland (3)

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# The delay line with a surface acoustic wave for an oscillator of electric signals in some sensors

***Abstract.** The article deals with the issue of delay lines on the basis of surface acoustic waves for the application in single mode oscillators. Based on the theoretical analysis concrete delay lines are proposed. In the contribution, there is given a theory of design of a symmetrical mismatched and matched delay line for a single-mode oscillator of electrical signals on the basis of which the there were designed and realized acoustoelectronic components for sensors of non-electrical quantities. In the article, the delay lines with surface acoustic waves for single-mode oscillators are investigated and the single-mode oscillation conditions of oscillators are derived and based on the deduced theory the concrete delay lines are proposed for various purposes of usage. From the experimental results it can be stated that in case of all of six designed and implemented delay lines, there was confirmed a single-mode.*

***Streszczenie.** W artykule omówiono zagadnienie linii opóźniających zrealizowanych na podstawie akustycznych fal powierzchniowych do zastosowania w oscylatorach jednomodowych. Na podstawie analizy teoretycznej proponowane są konkretne linie opóźniające. W tekście przedstawiono zagadnienie teoretyczne projektowania dopasowanej i niedopasowanej symetrycznej linii opóźniającej dla oscylatora sygnałów elektrycznych, w oparciu o które zaprojektowano i zrealizowano elementy akustoelektroniczne dla czujników wielkości nieelektrycznych. W artykule omówiono linie opóźniające wykorzystujące powierzchniowe fale akustyczne dla oscylatorów jendomodowych, przedstawione są warunki oscylacji oscylatora jednomodowego oraz na podstawie wydedukowanej teorii proponowane są różne linie opóźniające dla różnych celów użytkowania. Wyniki eksperymentalne pozwalają stwierdzić, że dla każdego z sześciu zaprojektowanych i zrealizowanych linii opóźniających potwierdzono jednomodowość.* ***(Linia opóźniająca z powierzchniową falą akustyczną dla oscylatora sygnałów elektrycznych wybranych czujnikach)***

**Keywords:** delay line, oscillator, surface acoustic wave, transducers.
**Słowa kluczowe:** linia opóźniająca, powierzchniowa fala akustyczna, przetworniki.

### Introduction

As selective elements of oscillators of harmonic vibration besides the band-pass filters are also used delay lines (DL) and resonators as a perspective a coustic-electric components based on surface acoustic waves (SAW). From the stability point of view we can classify these oscillators among the ones with volume acoustic waves and LC oscillators.

In the article, the DL with SAW for single - mode oscillators.

### The oscillator with delay line

The basic principle of function of oscillator with delay line is represented on the next figure (Fig. 1). The delay line (4) with SAW plugged in the feedback of amplifier (2) is a basic element. Circuits (1, 3) serve to match impedance of the abovementioned to the impedance of the electronic circuitry.

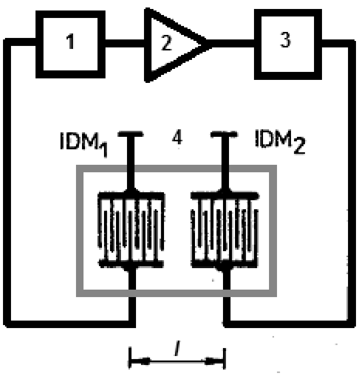



Fig.1. Bloc diagram of oscillator.

Because the previous signal from the input to the output of DL is delayed, examined oscillators are ones with delayed feedback. The theory of these oscillators is well known in the literature [1].

Different situation is in the case of DL with SAW, where DL themselves have narrow transmission band and their parameters differ fundamentally in this range. Physical distinctiveness of functioning of listed components which are related with phenomena of excitation, extension and reflection of SAW cause that in addition to delay, the DL´s have specific frequency dependencies of input and output admittances. Their replacement with the lumped elements RLC circuit or broad - band DL with outer selective LC is mentioned only very general.

### The oscillator with mismatched delay line

The used delay line with SAW as a selective element of oscillator can be symmetrical or non-symmetrical. Symmetrical DL is characterized by the same input and output IDT while non-symmetrical DL has the input IDT with small number of electrodes (broadband) and output IDT with big number of electrodes (narrowband). In the contribution we will only deal with the symmetrical DL. For simplification we will assume that input and output admittance of active element, taking the load into consideration, is equal and real i.e. $g_1 = g_2 = g$. The imaginary part of input and output admittance of element (taking the load into consideration) can be included to static capacity of IDT of DL with SAW.

By the solution of complex equation (1) we determine the parameters of natural oscillations

$$K(j\omega) = 1. \tag{1}$$

The depicted equation can be dissolved to the balance of phase equation

$$\frac{\omega l}{v} + \varphi_e = 2\pi k \tag{2}$$

and the equation of modules balance

$$K_0 K_e(\omega) K_1(\omega) K_2(\omega) = 1, \tag{3}$$

where: $K_0$ – coefficient of loop amplification consisted of amplifier and DL, $K_e(\omega)$, $K_1(\omega)$ and $K_2(\omega)$ – module characteristics of amplifier, input and output IDT, $l = vt_0$ – the distance between input and output IDT centres, $v$ – velocity of SAW propagation, $t_0$ – delay of DL, $\varphi_e$ – change of phase of electric signal in IDT and amplifier, $k$ – positive integer.

Adequate choice of oscillator's active element amplification enables to attain the phase balance and appropriate geometrical arrangement of DL enables to attain the balance of arguments.

For a sufficiently long distance *l*, the value of $\varphi_e$ is fundamentally smaller than $\omega l/v$ and so $\varphi_e$ do not need not be considered in the first approximation. Then the frequencies on which the oscillations are emerged can be determined from the equation (2). Applying the above we get:

(4) $$\omega_k = \frac{2\pi v}{l}k\ , \quad f_k = \frac{k}{t_0}.$$

The indicated frequencies make up the discrete spectrum with the interval between single frequencies (Fig. 2b)

(5) $$\delta f = \frac{1}{t_0}\cdot$$

With an appropriate choice of arrangement and IDT geometry, the single - mode oscillation regime can be obtained. In case of a symmetrical DC, i.e. the input and output IDTs are equal and have *N* sections of distance $\lambda_0\left(\lambda_0 = \frac{v}{f_0}\right)$, a module characteristics of DL nearby synchronised frequency can be sufficiently exactly approximated by the function in the form $\frac{(\sin^2 x)}{x^2}$, where $x = N\pi\frac{(f - f_0)}{f_0}$. Zeros of module characteristic match the values $x = \pm\ n\pi,\ (n \neq 0)$. Frequency intervals between zero values are given by the formula (Fig. 2)

(6) $$\Delta f = \frac{f_0}{N} = \frac{1}{\tau}.$$

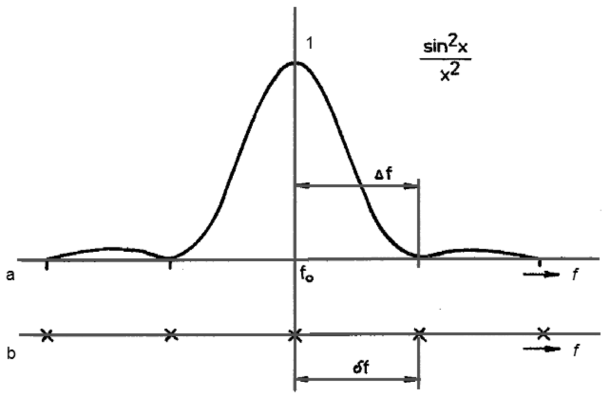



Fig.2. a) Module characteristics of IDT, b) The frequency at which the condition of balance of arguments is fulfilled

Then, from the relations (5) and (6), it results that ($\delta f = \Delta f$):

(7) $$P_0 = N\,,$$

can be obtained, where $P_0 = \frac{l}{\lambda_0}$ and the distance $l$ is expressed in multiples of $\lambda_0$.

For the LC oscillators the sharpness of argument characteristics is determined by the time constant of circuit $\tau$, which is a function of quality factor of a resonance system $\Theta$ and of working frequency $\omega_0$ according to the relation:

(8) $$S_f = \tau_{LC} = \left|-\frac{d\Theta}{d\omega}\right|_{\omega_0} = \frac{2\Theta}{\omega_0}.$$

For the oscillators with DL and SAW applies:

(9) $$S_f = t_0 = \frac{l}{v} = \frac{2\pi P_0}{\omega_0}.$$

Applying the previous relations we can introduce a term of quality factor of resonance system of oscillator with SAW and applies the following:

(10) $$\Theta = \pi P_0 = \frac{\pi l}{\lambda_0}.$$

From given equation (10) it results that maximum value of quality factor is set by realisable value of delay which depends on the propagation velocity of SAW and on the technological possibility to grow mono - crystals, as well as on the operating frequency $\omega_0$, which upper limit is given by the possibilities of photolithographic technology.

The very appropriate property of oscillators with SAW is the possibility to independently convert module and argument characteristic of DL.

For piezoelectric materials with low electromechanical coupling coefficient $K^2$ (e.g. $SiO_2$), provided the components of convertors´ admittance are mutually measurable with the components of the input and output admittance of active element and at the fulfilling of inequality

(11) $$4K^2 N_i\frac{(1+\chi_i)}{\pi} << 1,$$

where: $\chi_i = \frac{g_i}{G_i}$ is the matching coefficient, we reach the following relation to set the optimal value of relative IDT centres distance, at which the single - mode oscillation regime emerges at working frequency $\omega_0$. Applying it we get:

(12) $$P_0 = \frac{2k-1}{2} + \frac{2K^2}{\pi^2}\left[N_1(1+\chi_1) + N_2(1+\chi_2)\right].$$

It results from the equation (12) that optimal distance of centres of IDT in DL with SAW approaches the odd number of multiples $\frac{\lambda_0}{2}$ at the frequency $\omega_0$ ($g_i = \omega_0 C_{Ti}$) and in case of symmetrical DL ($N_1 = N_2$)

(13) $$P_0 = \frac{4k-1}{4} + \frac{4K^2}{\pi^2}N.$$

It results from the equation that optimal distance of IDT centres in this case approaches the odd number of multiples $\frac{\lambda_0}{4}$ at the frequency $\omega_0$.

**The oscillator with matched delay line**

To improve the characteristics of oscillators with DL with SAW matching (compensation) of IDT static capacitance is used, while the use of compensation circuits has certain advantages and disadvantages [3]. Among the advantages are the decrease of inserted damping and increase of DL transmission coefficient. The disadvantage is the worsening of long - term stability of oscillator frequency as a consequence of instability of matching circuits. The optimal distance will be calculated from the relation

$$P_0 = k - \frac{1}{8} + \frac{2K^2}{\pi} N_1 - \frac{\omega_0 - \omega_{p2}}{8K^2 N_2 (1 + \chi_2)\omega_0}. \qquad (14)$$

**The design and experimental results of symmetrical delay line**

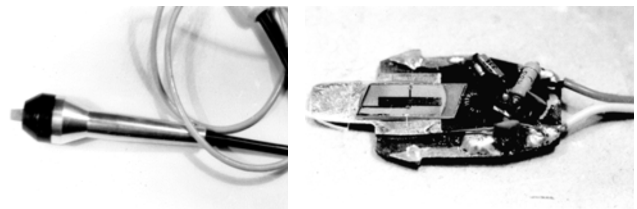
In the present paper the DL with SAW for single mode oscillators are investigated.

The main benefit of this article is based on:

- The initial elaboration of the theory of a synthesis of symmetrical DL with SAW. The referred elaborated theory is the baseline theory according to which are designed the important components of acoustoelectronic components – delay lines.
- The verification and accuracy of the proposed procedure. Based on the given theory it was designed and implemented a temperature sensor on the principle of a delay line, a sensor of displacement and other sensors for measurement of non-electrical quantities.
- The development of knowledge in a given field of science and its general applicability, i.e. for other sensors of non - electrical quantities.
- The experimental results that confirm the single - mode oscillation mode for all designed and implemented delay lines and thereby confirming the previously mentioned benefits.

Other delay line DL PLO 41 is symmetrical and mismatched, which was implemented for the sensor of temperature (Fig. 3). As a material of the pad a special LST – cut (due to its higher sensitivity), $X$ – direction of propagation of $SiO_2$ has been chosen. The thickness of the substrate is 0.5 mm.

The design drawing is in the Fig. 4 realized DL with SAW is in the Fig. 5 and the inserted damping dependency on the frequency is in the Fig. 6. Some calculated and measured parameters are listed in the Table 1.



*a)* *b)*

Fig.3. Realized thermosensor based on SAW: a) construction execution, b) delay line and electronics

One of the sensors designed for on the basis of Chapter 1, was the flow sensor suitable for precise laboratory measurements as well as for normal operating measurements. Since the components of SAW are extremely sensitive to the temperature change (of the order of $10^{-4}$ K), this has been applied in the implementation of the flow sensor. The flow of liquid (or gas) results in a change temperature of pad, which is placed on the flow meter. On this pad is made an acoustic-electronic component that reacts to temperature change (delay line or resonator).

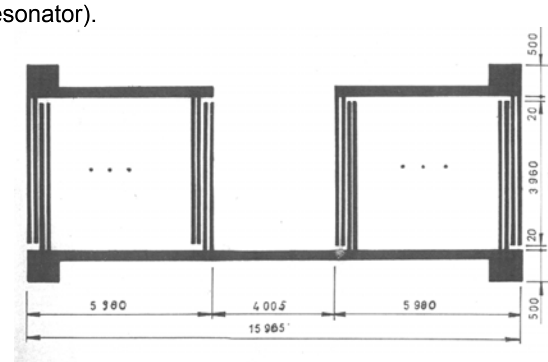



Fig.4. Delay line DL PLO 41 design drawing (all dimensions in μm)

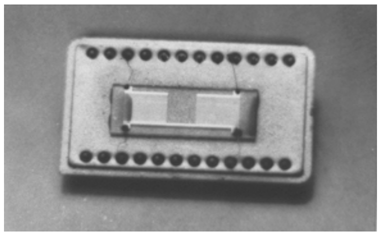


Fig.5. Photography of realized DL PLO 41

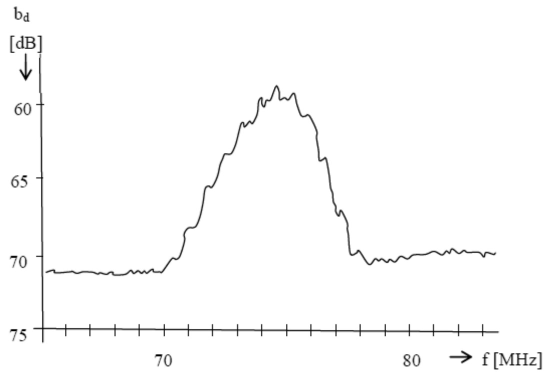



Fig.6. The inserted damping dependency on the frequency for DL PLO 41

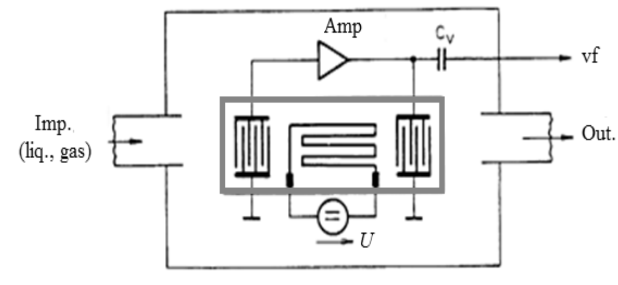



Fig.7. The block diagram of the flowmeter.

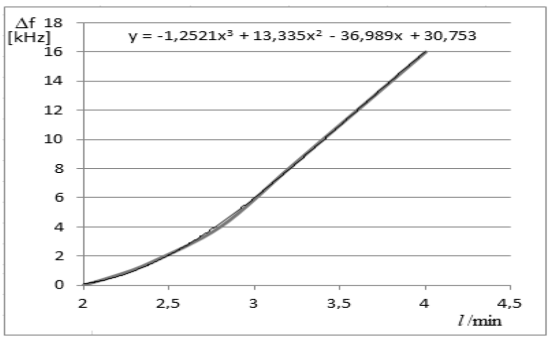



Fig.8. The flow characteristics of the oscillator with SAW.

The block diagram of the flowmeter is presented in the Fig.7. Flow characteristic of the implemented oscillator based on SAW (flow dependence on frequency) is shown in Fig.8.

**Conclusion**

In the contribution the way of design of symmetrical mismatched and matched DL for single – mode oscillator of electric signals is worked up. It can be stated based on the given experimental results that the single – mode oscillation regime has been confirmed in a six of total designed and realized DL for pressure, temperature, and flow sensors. The given table (Tab. 1) presents the calculated and measured values in only one sample applied thermo-sensor.

Table 1. The parameters of realised delay lines.

| Parameter | PLO 41 | Note |
|---|---|---|
| $v_{ef}$ [ms$^{-1}$] | 3445 | |
| $K^2$ | 0.0482 | |
| $C_s'$ [pFm$^{-1}$] | 464.4 | specific capacity of section |
| $\lambda_0$ [$\mu$m] | 40 | $\lambda_0 = \frac{v_{ef}}{f_0}$ |
| $l_e = l_0$ [$\mu$m] | 5 | electrode and gap width |
| $f_{oc}$ [MHz] | 86.125 | calculated |
| $f_{om}$ [MHz] | 86.11 | measured |
| N | 149.5 | |
| n | 300 (double) | n = 2N + 1 |
| $l'$ [$\mu$m] | 5980 | $l' = N\lambda_0$ |
| l [$\mu$m] | 9990 | $l = P_0\lambda_0$ |
| $P_0$ | $\approx$ 250 | |
| k | 250 | |
| $C_{Tc}$ [pF] | 376 | $C_{Tc} = C_s' wN$ |
| $C_{Tm}$[pF] | 370 | measured |
| $Q_c$ | 785 | $Qc = \pi P_0$ |
| $Q_m$ | $\approx$ 780 | measured |
| $b_i$ [dB] | 14 | inserted damping |
| w [$\mu$m] | 3960 | aperture |

Development of the control and automation of production processes in industry and the energy sector has requirements on the measuring equipment and technical devices for measuring of the non - electrical quantities. For this purposes the most used sensors are temperature, pressure and flow.

These requirements are fulfilled by realized sensor on the SAW base that can be used to control of the temperature rise of electrical machines parts like bushings, transformer windings or insulating medium itself.

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***Authors:** Assoc. Prof. Milan Šimko, PhD., Ing. Milan Šebok, PhD., Assoc. Prof. Milan Chupač, PhD., Assoc. Prof. Miroslav Gutten, PhD., Ing. Daniel Korenčiak, PhD: Faculty of Electrical Engineering of the University of Žilina, Department of Measurement and Applied Electrical Engineering, Univerzitná 1, 010 26 Žilina, Slovak republic, e-mail:milan.sebok@fel.uniza.sk; M.Sc. Katarzyna Piotrowska, Institute of Technological Systems of Information, Lublin University of Technology, ul. Nadbystrzycka 38a,20-618 Lublin, Poland; prof. Paweł Zhukowski, dr hab. Tomasz N. Koltunowicz: Politechnika Lubelska, Wydział Elektrotechniki i Informatyki, Katedra Urządzeń Elektrycznych i Techniki Wysokich Napięć, ul. Nadbystrzycka 38a,20-618 Lublin, Poland, E-mail: pawel@elektron.pol.lublin.pl.*

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