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# The theoretical synthesis and design of symmetrical delay line with surface acoustic wave for oscillators with single-mode regime of oscillation

***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.*

***Streszczenie:*** *W artykule przedstawiono zagadnienie akustycznych fali powierzchniowych w liniach opóźniających w pojedyńczych oscylatorach. Na podstawie analizy teoretycznej zaproponowano konkretne rozwiązania linii opóźniających (**Synteza i projektowanie linii opóźniających z akustyczną falą powierzchniową w pojedyńczych oscylatorach**).*

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

## 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 acoustic-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. The quality factor of vibrating system of oscillators with SAW is in the range from 100 to 10 000 while these oscillators work with the basic harmonic in the frequency range from 10 MHz to 1,5 GHz. Their main advantages are small dimensions, low weight, high mechanic strength, low sensibility to vibrations and a possibility to construct oscillators without using inductors. That is just what increases the perspectives of their manufacturing and the wide possibilities of their usage in radio electronics, telecommunications and concurrently the necessity to work out the questions connected with their theory and manufacturing

In the article, the DL with SAW for single-mode oscillators are investigated and the single-mode oscillation conditions of oscillators are derived and based on the deduced theory the concrete DL are proposed for various purposes of usage.

## 1. 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 with SAW (3) plugged in the feedback of amplifier (2) is a basic element. Piezoelectric single crystal base (e.g. Y-cut, Z-direction of propagation of $LiNbO_3$, ST, X-$SiO_2$ etc.) on which are the input and output interdigital transducers ($IDT_1$) and ($IDT_2$) fabricated by photolithographic technology. Matching circuits (1, 3) serve to adjust the abovementioned transducers.

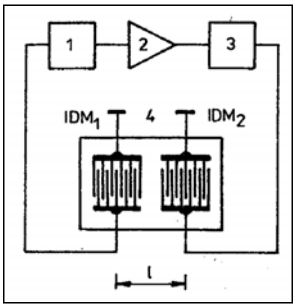


Fig. 1 Bloc diagram of oscillator:1, 3 – matching circuits; 2 – amplifier; 4 – delay line with SAW

Because the previous signal from the inpu t 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, 2], nevertheless the achieved results concern especially to the oscillators with broadband DL in which the necessary frequency selectivity is secured with additional circuits (e.g. LC), while in the frequencies range of possible applications, the DL parameters do not differ significantly. 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.

It can be considered as an advantage that with the oscillators with SAW, to compensate their static capacity, compensational inductors plugged in to input and output IDT do not have to be used. By leaving them out, the voltage and current coefficients of transfer substantially decrease, which in the end leads to the necessity of bigger amplification in oscillator's active element and thereby to the different action in the process of proposing the DL with SAW.

In the next part we will examine firstly the oscillators without compensation inductors (mismatched DL with SAW) and then the oscillators with matched DL.

### 1.1 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

(1) $$K(j\omega) = 1.$$

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

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

and the equation of modules balance

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

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 balance of modules and appropriate geometrical arrangement of DL enables to attain the balance of arguments.

In sufficiently big distance $l$, the value of $\varphi_e$ is fundamentally smaller than $\omega l / v$ and so $\varphi_e$ need not be considered in the first approximation. Then the frequencies on which the oscillations are emerged can be determined from the equation (2).

Applies:

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

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

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

With an appropriate choice of arrangement and IDT geometry, the single-mode oscillation regime can be obtained. In case of symmetrical DC, i.e. the input and output IDT are equal and have $N$ sections of distance $\lambda_0 \left( \lambda_0 = \frac{v}{f_0} \right)$, a module characteristics of DL near by 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.2a)

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

There can be stated from the presented facts, that the only condition of single-mode oscillation regime is that all the frequencies of discrete spectrum (5) need to be identified with except for the synchronous frequency, with zero values of DL module characteristics: $\delta f = \Delta f$.

Then, from the relations (5) and (6), it results that

(7) $$t_0 = \tau$$

and after modifying the relation

(8) $$P_0 = N, \qquad )$$

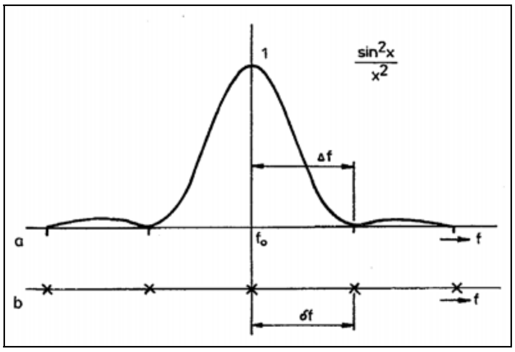


Fig. 2 a) Module characteristics of IDT; b) the frequency at which the condition of balance of arguments is fulfilled

can be obtained, where $P_0 = \frac{l}{\lambda_0}$ and the distance $l$ is expressed in the multiples of $\lambda_0$. For the single-mode oscillation regime, the DL delay $(t_0)$ and the delay created in IDT $(\tau)$ must be equal (at least approximately), from which it results that the distance of IDT centres must be equal to the IDT length.

It is known that the oscillator's frequency stability is determined by the sharpness of argument characteristics of its resonance system at the working frequency $\omega_0$. The sharper is this characteristic the higher is the stability of frequency.

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 resonance system $\Theta$ and of working frequency $\omega_0$ according to the relation:

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

For the oscillators with DL and SAW applies:

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

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

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

From given equation (11) 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 (Fig.3). Two of the represented IDT are in the figure (Fig.3a), for which the condition (8) and corresponding module and argument characteristic is fulfilled. Three times increase of delay $t_0$ at the same dimensions of IDT $(P_0 = 3N)$ causes three times increase of argument characteristic's sharpness (equation 10), while the module characteristic does not change. In the third case (Fig.3c), the delay and argument characteristics remain the same as in the figure (Fig.3b), but the length of each of IDT increases three times. It causes the narrowing of DL band-pass in comparison with two previous cases. In the oscillator with given DL, the oscillations are possible only at one frequency (in DL – Fig.3b - the balance of arguments and modules condition is fulfilled at various frequencies) and this oscillator has higher frequency stability than the oscillator with DL in the Fig.3a. The increase of frequency stability is achieved by the fact that at the increase of IDT proportions and thus also at the increase of delay $t_0 = \frac{l}{v}$ (while $P_0 = N$ is still valid), the oscillator becomes less sensitive to the changes of electric phase shift (equation 2).

More accurate single-mode oscillation condition can be determined from the complete equation (2). Substitution for $\varphi_e = \psi_1 - \psi_2$ gives the equation:

(12) $$P_0 = k - \frac{(\psi_1 + \psi_2)}{2\pi}$$

where: $\psi_1 = arctg \frac{(b_i + B_i)}{(g_i + G_i)}$, $g_i$ and $b_i$ are real and imaginary part of intrinsic admittance of i-level gate of linear oscillator's part without the backward coupling of circuit, i.e. without DL with SAW, $G_i$ and $B_i$ are real and imaginary part of input admittance of i-level gate of DL with SAW near short-circuit of the second (j-level) gate (i = 1, 2) [3].

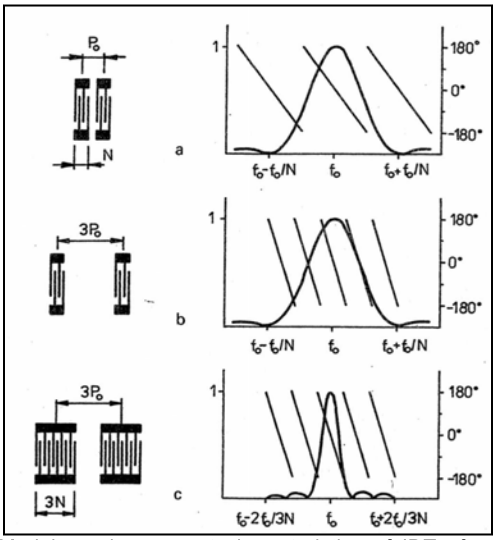


Fig. 3 Module and argument characteristics of IDT of various configurations

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

(13) $$4K^2 N_i \frac{(1+\chi_i)}{\pi} << 1,$$

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 $\omega_0$. Applies:

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

It results from the equation (14) that optimal distance of centres of IDT in DL with SAW approaches the odd number of multiples $\lambda_0 / 2$ at the frequency $\omega_0$.

If the input and output conductance of active element equals the corresponding susceptancies, i.e. $g_i = \omega_0 C_{Ti}$, then:

(15) $$P_0 = \frac{4k-1}{4} + \frac{2K^2}{\pi^2}(N_1 + N_2)$$

and in case of symmetrical DL ($N_1 = N_2$)

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

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

**2.2 The oscillator with matched delay line**

To improve the characteristics of oscillators with DL with SAW matching (compensation) of IDT static capacity is used, while the use of compensation circuits has certain advantages and disadvantages. Among the advantages are the decrease of inserted damping and increase of DL transmission coefficient. It allows to achieve higher output power and to increase the effectiveness compared with the oscillator with unsuited DL. The disadvantage is the worsening of long-term stability of oscillator frequency as a consequence of instability of matching circuits. In simple cases we can attain the adjustment by serial connection of compensation inductor to the IDT clamps (at the low value of real part of the input or output admittance of active element) or by parallel connection (at the high value of real part). The natural resonance frequency of created resonance circuit (i.e. serial or parallel) has to be near to the frequency:

$$\omega_p = 1 / \sqrt{L_k C_T} \quad .$$

(17)

To ensure single-mode oscillation at $g_1 = g_2 = g$, $\omega C_T - \frac{1}{\omega L_k} = 2C_T(\omega - \omega_p) = g$ for the relative distance of IDT centres, the relation

(18) $$P_0 = k,$$

where k is positive integer is valid.

From the equation (18) it results the fact that optimal distance of IDT centres to reach single-mode oscillation must equal the integral multiples of $\lambda_0$. If the resonance frequency of adapter circuits differs from $\omega_0$, then the optimal relative distance of IDT centres can be calculated from the equation:

(19) $$P_0 = k - \frac{1}{8K^2\omega_0}\left[\frac{\omega_0 - \omega_{p1}}{N_1(1+\chi_1)} + \frac{\omega_0 - \omega_{p2}}{N_2(1+\chi_2)}\right].$$

To increase the output resistance of linear resonance scheme of oscillator (i.e. active element and DL) and also to increase the output signal filtration we can match only the output IDT itself. In this case the optimal distance will be calculated from the relation:

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

**3 The design of symmetrical delay lines, experimental results and discussion**

Based on the previous theoretical consideration, the symmetrical delay lines PSO 40 have been designed and realised and applied at the thermosensor and PLO 39 for flow meter based on SAW.

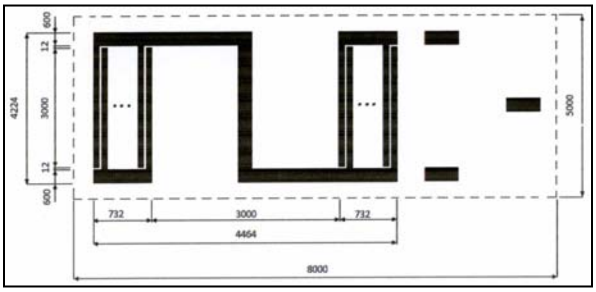

Fig.4 Delay line PSO 40 design drawing (all dimensions in μm)

The delay line PSO 40 is symmetrical mismatched DL. As a substrate material a special LST-cut (because of its higher sensibility) has been used, X-direction of propagation-$SiO_2$. The design drawing is in the fig.4, realised 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 tab.1.

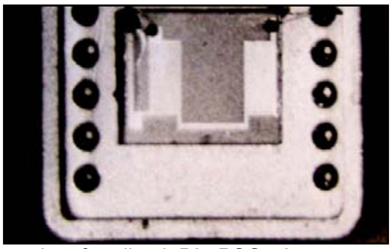
Fig. 5 Photography of realised DL PSO 40

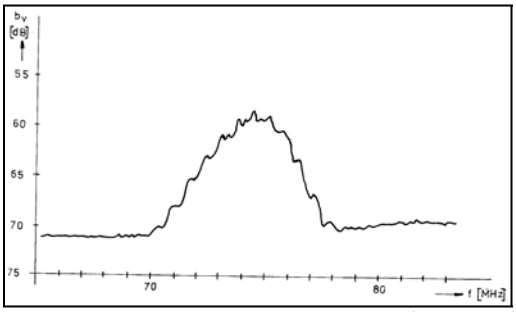

Fig. 6 The inserted damping dependency on the frequency for DL PSO 40

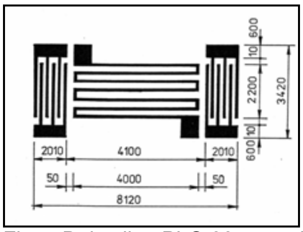

Fig. 7 Delay line PLO 39 design drawing (all dimensions in μm)

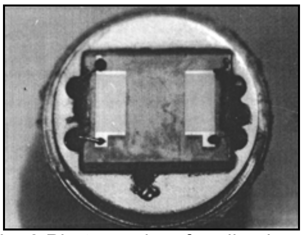
Fig. 8 Photography of realised DL PLO 39

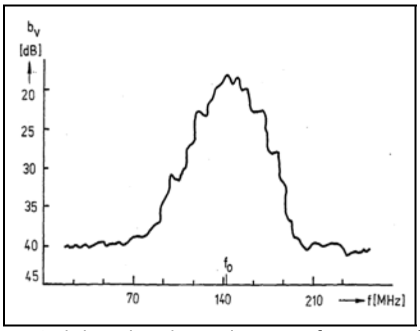

Fig. 9 The inserted damping dependency on frequency for DL PLO 39

The second designed and realised symmetrical mismatched DL for the single-mode oscillator is DL PLO39, the design and structure of which are shown in fig.7. The photograpy of realised DL is in the fig.8 and the inserted damping dependency on frequency is in the fig.9. The substrate was fabricated from Y-cut, Z-direction of propagation-$LiNbO_3$. Some of the calculated and measured values are listed in the table 1.

**The 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 single-mode oscillation regime has been confirmed in total of six of designed and realised DL. In the given table (Tab.1) are presented the calculated and measured values of two samples applied in the thermo-sensor and flow-meter.

Tab. 1 The parameters of realised delay lines

| Parameter | PSO 40 | PLO 39 | Note |
|---|---|---|---|
| $v_{ef}$ [$ms^{-1}$] | 3357 | 3990 | |
| $K^2$ | 0,0022 | 0,0482 | |
| $C_s'$ [$pFm^{-1}$] | 68 | 696 | specific capacity of section |
| $\lambda_0$ [μm] | 50 | 28 | $\lambda_0 = \frac{v_{ef}}{f_0}$ |
| $l_e = l_0$ [μm] | 12 | 10 | electrode and gap width |
| $f_{oc}$ [MHz] | 76,09 | 142,5 | calculated |
| $f_{om}$ [MHz] | 76,06 | 142,7 | measured |
| N | 15 | 50 | |
| n | 31 | 101 | n = 2N + 1 |
| $l'$ [μm] | 732 | 1400 | $l' = N\lambda_0$ |
| l [μm] | 3732 | 6110 | $l = P_0\lambda_0$ |
| $P_0$ | ≈ 83 | ≈ 220 | |
| k | 83 | 220 | |
| $C_{Tc}$ [pF] | 3,06 | 78 | $C_{Tc} = C_s' wN$ |
| $C_{Tm}$[pF] | 2,62 | 80 | measured |
| $Q_c$ | 261 | 690 | $Qc = \pi P_0$ |
| $Q_m$ | ≈ 260 | ≈ 695 | measured |
| $b_i$ [dB] | 58 | 18 | inserted damping |
| w [μm] | 3000 | 2240 | aperture |

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