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Design of Surface Acoustic Wave Compressors with Interdigital Transducers

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An algorithm suitable for the computer aided design of the surface acoustic wave (SAW) compressor with interdigital transducers (IDT) is presented. The geometry of the uniform interdigital transducer is calculated first. Starting from the desired impulse response, the electrode positions and lengths (apodisation) of the dispersive IDT are determined. The last algorithmic step is the design of the matching networks between the IDTs and the load and the generator. The algorithm takes as input the central frequency, bandwidth, delay dispersion, substrate, compressor and electrode type, weighting function, and load and generator resistances. The output results are the electrode positions and geometry, and the element values of the matching networks. The algorithm has been exemplified by a filter design with the central frequency of 60 MHz and dispersion of 1μs, within the 10 MHz bandwidth, fabricated on ST-quartz. The delay characteristic of the fabricated filter is measured and the experimental results satisfy the filter specification verifying the proposed algorithm and software.

Key words: **SAW element, SAW filter, SAW compressor, expander, design, algorithm.**

Introduction

SURFACE acoustic wave compressors, or down chirp filters, or dispersive delay lines, have found numerous applications in modern communication and signal processing systems due to their compact structure, high sensitivity, small size, outstanding stability, fast response and above all their ability to be incorporated in complex data processing systems. They are actually matched filters, matched to the linear frequency modulated signals. SAW compressors are used in pulse compression radars, Doppler radars, single-stage real-time Fourier-transform processors for the spectrum analysis of signals, two-stage real-time Fourier-transform processors for spectrum analysis, two-stage real-time Fourier-transform processors for real-time on-line filtering, and in variable delay lines [1]-[3]. The rapid development of SAW technology enables the production of compressors with large time-bandwidth (TB) products which are not attainable with other technologies.

Surface acoustic waves were discovered in 1885 by Lord Rayleigh [4], and are often named after him: Rayleigh waves. A surface acoustic wave is a type of mechanical wave motion which travels along the surface of a solid material. The velocity of acoustic waves is typically 3000 m/s, which is much lower than the velocity of the electromagnetic waves. A basic SAW device was originally developed in 1965 [5]. It consists of two interdigital transducers on a piezoelectric substrate such as quartz. The IDT consists of interleaved metal electrodes which are used to launch and receive the waves, so that an electrical signal is converted to an acoustic wave and then back to an electrical signal. Starting around 1970, different kinds of SAW devices have been developed for applications in pulse compression radars, communications and signal processing systems, mobile radio, and cellular telephones. New high-performance SAW filters emerged and vast numbers are now produced, around 3 billion annually. In the last two decades SAW devices have found numerous different applications outside their conventional fields of application, communications and signal processing, as sensors of different types: temperature, pressure, stress, chemical and bio sensors [6, 7].

The delay and amplitude characteristics of a SAW compressor are presented in Fig.1, where $\Delta\tau$ denotes the dispersion T , and B the bandwidth. The figure of merit of the compressor is a so-called TB-product. If the input signal is a linear frequency modulated one, the output signal is the compressed pulse, as shown in Fig.2a. The geometry of the compressor is designed in the way that higher frequencies of the input signal, which come later to the input, pass through the filter quicker than lower frequencies which come first. The magnitude of the compressed pulse is a linear function of the TB-product.

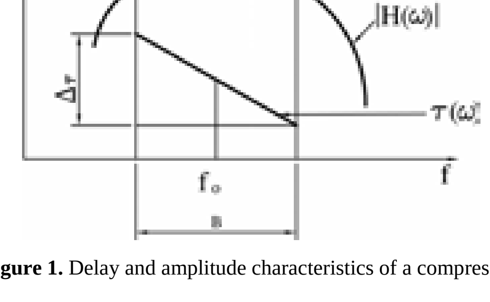

Figure 1. Delay and amplitude characteristics of a compressor.

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SAW compressor can be realized in two different forms: as a SAW transversal filter with two IDTs or as a reflective array compressor (RAC). The first form is used for lower frequencies and smaller TB-products (<1000). SAW compressor with two IDTs can be made in three different ways: with one uniform and one dispersive IDT, Fig.2a, with both dispersive IDTs, Fig.2b, and with both dispersive IDTs but slanted against the horizontal axes Fig.2c.

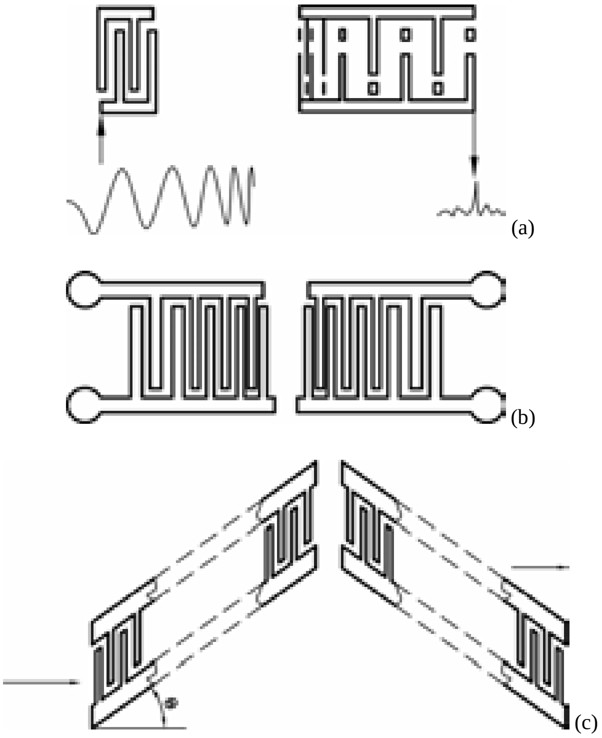

Figure 2. Basic configurations of IDT compressors: (a) one uniform and one dispersive IDT, (b) two dispersive IDTs, (c) two slanted dispersive IDTs.

The dispersive delay line, which has the delay characteristic of the opposite direction, e.g., a smaller delay at lower frequencies (so-called up chirp), is known as the expandor.

Commonly used substrate materials are ST-cut quartz and lithium niobate. Lithium niobate is often used because of its high coupling coefficient between the mechanical and electrical variables. ST-quartz has substantial advantages with respect to the influence of the second-order effects, e.g., lower bulk wave generation, lower acoustic reflection, and better temperature stability. Hence, ST-quartz may be preferred for dispersive designs except if the specifications call for a low insertion loss or wide bandwidth.

In this paper, the design and the realization of the compressor with one uniform and one dispersive IDT is considered. An algorithm suitable for the computer aided design of the compressor is presented. The algorithm consists of several steps. In the first step, the number of the electrodes of the uniform transducer is calculated. In the second step, the number and the positions of the electrodes of the dispersive transducer are determined. After that, the design of the matching networks between the IDTs, and the load and the generator, is carried out.

The algorithm for the design of the SAW compressor

The first step in the design of the SAW compressor is the choice of the substrate and configuration of the compressor according to the given specifications: the center frequency, bandwidth, dispersion, substrate, transfer function, compressor and electrode type, weighting function, load resistance, and generator resistance. For relative bandwidths lower than 25%, ST-quartz and configuration with one uniform and one dispersive IDT can be used. In that case, the input transducer is uniform with a relatively small number of electrodes (which means that it has wide bandwidth) of equal lengths. The bandwidth of the compressor is determined by the bandwidth of the dispersive IDT.

The centers of the electrodes of the input IDT are at distances of $\lambda_0/2$, where λ_0 denotes the wavelength which corresponds to the center frequency f_0. If single electrodes are used, the electrode width is $0.25\lambda_0$, and $0.125\lambda_0$ if double electrodes are used. The number of electrodes is a function of the relative passband B/f_0 The maximum value of the relative passband with a minimal insertion loss of 6 dB is determined by the substrate type and is given by

$$(B/f_0)_{\max} = 2k/\sqrt{\pi}\,, \tag{1}$$

where k is the electromechanical coupling coefficient [8]. If the desired relative passband is smaller than the optimal one, the number of electrodes in a single electrode case can be calculated as [8]:

$$N_{\mathrm{ei}} = 1 + 2\,f_0/B\,. \tag{2}$$

The length of the input transducer is, then,

$$L_{\mathrm{i}} = (\,f_0/B + 0.25)\lambda_0\,. \tag{3}$$

If the desired relative passband is greater than the optimal one, the number of electrodes in a single electrode case can be calculated as [8]:

$$N_{ei} = 1 + \frac{2B}{\pi f_0^2 C_s R_a(\,f_0)}\,, \tag{4}$$

where C_s is the capacity per electrode pair and $R_a(\,f_0)$ is the acoustic resistance of the transducer at f_0. In that case, the insertion loss is increased.

The electrodes of the output transducer are apodised, i.e., have different lengths (overlaps) and with different (non-uniform) positions. The electrode positions are determined by the linear frequency dependence of the group delay. Apodisation suppresses the oscillations of the amplitude characteristic in the stop band. The essential and most complex part of the dispersive IDT design is the determination of the electrode positions. Since the electrode positions are calculated from the impulse response of the transducer $h_0(t)$, it should be found first. The impulse response is found from the transfer function of the transducer $H_0(\,f)$ as the inverse Fourier transform:

$$h_0(t) = (\mathrm{FT})^{-1} H_0(t) \tag{5}$$

while $H_0(\,f)$ can be found from the specified transfer function of the whole compressor $H(\,f)$ using the relation:

$$H(\,f) = H_i(t)\cdot H_0^*(\,f)\,, \tag{6}$$

where $H_i(\,f)$ denotes the transfer function of the input uniform transducer and can be easily found from the geometry of the input transducer. Since $h_0(t)$ is infinite, it should be multiplied by a window function because the number of electrodes is finite. The next step is the determination of the necessary number of electrodes in the dispersive transducer N_0. In the single electrode case it is found from [9, 10]:

$$N_0 = 2\mathrm{c} f_0 T + 1, \tag{7}$$

where f_0 is the center frequency of the filter, T is the specified dispersion and c is the constant which depends upon the weighting used and usually is between 1.2 and 1.5. For high frequency filters and large dispersions, the number of electrodes is quite high. The ratio of the electrode width and gap is 1 for values of N_0 up to few hundreds. For larger N_0, the constant electrode width of $0.7\lambda_{\min}/4$ is used.

The distance between the transducers is in the range from $10\lambda_0$ to 10 times the wave front width. The electrode positions, for the single electrode case, are determined iteratively from the impulse response where its phase is 0 or π, Fig.3:

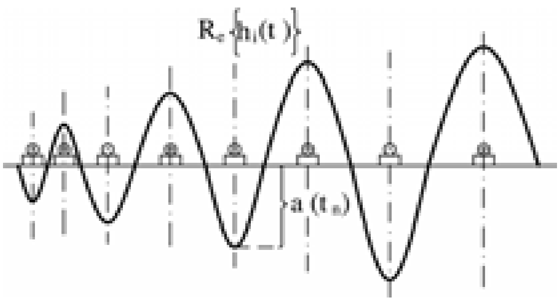

Figure 3. Electrode positions for a given impulse response $h_0(t)$.

$$x_n - x_{n-1} \cong v(t_n - t_{n-1}) - a\Delta v / v, \tag{8}$$

where a is the electrode width, v is the wave velocity of the free surface of the substrate, and $\Delta v / v$ relative velocity change due to the electrodes. If the electrode width is equal to one half of the distance between the electrodes (metal/gap =1), e.g., $a = 0.5(x_n - x_{n-1})$, the electrode positions can be calculated using the simpler relation:

$$x_n = t_n v_{\mathrm{ef}}, \tag{9}$$

where:

$$v_{ef} = v\left(1 - \frac{\Delta v}{2v}\right) \tag{10}$$

The time samples t_n are the solutions of the equation:

$$\phi(t_n) = n\pi + \mathrm{const.}, \tag{11}$$

where $\phi(t)$ is the phase of the impulse response. The impulse response of the compressor is given by

$$h_0(t) = a(t)\mathrm{e}^{\mathrm{j}2\pi(f_0 t \pm (B/2T)t^2)},\ a(t) = 1$$

for

$$|t| \le T/2 \text{ and } h_0(t) = 0 \text{ for } |t| \ge T/2. \tag{12}$$

The electrode positions are now calculated using (9), (11) and (12):

$$x_n = v_{\mathrm{ef}}\, f_0 \frac{T}{B}\left(-1 + \sqrt{1 - \frac{B(0.5N_0 - n)}{Tf_0^2}}\right), \tag{13}$$

where the constant in (11) is chosen in such a way that $x_n = 0$ is in the center of the transducer.

The next step is the determination of apodisation. The first reason for apodisation is due to the fact that there are more high frequency electrodes than low frequency electrodes. This means that the high frequency electrodes excite a stronger piezoelectric field than the low frequency electrodes. To compensate for that, the length of each electrode should be corrected by the factor $(f_0/f_n)^{3/2}$. The additional weighting (apodisation) should be used to eliminate the amplitude and phase ripples. The most common weighting function used is $\cos^2$ [10, 11] which gives the sidelobes suppression in the time domain of only 13 dB. However, in most radar applications of the compressor, the requirements call for the sidelobes suppression greater than 20 dB. In such cases an additional weighting is necessary and the Hamming and Taylor weighting (window) functions are used. This additional weighting function is realized either as a separate filter located after the compression filter or with an additional apodisation in the compressor. The length of the nth electrode W_n is given by

$$W_n / W_0 = (f_0 / f_n)^{3/2} \cdot a(t_n) / A, \tag{14}$$

where the additional weighting can be incorporated in $a(t_n)$, W_0 is the optimum width of the transducer aperture, A the maximum value of $a(t_n)$, and f_n the resonant frequency of the n th electrode:

$$f_n = f_0 \pm Bt_n / T. \tag{15}$$

The optimum width of the transducer aperture W_0, or the wave front width, and the matching network elements are determined from the given specifications for the amplitude and phase errors, triple transit echo suppression, insertion loss at the passband edges, and resistances of the generator and load.

The matching network between the output transducer and the load usually consists of a transformer, with the transformation ratio r, and an inductor L, as shown in Fig.4.

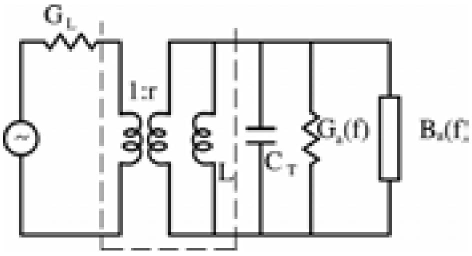

Figure 4. Equivalent circuit of the matching network and the output transducer.

G_{L} denotes the load conductance, $G_a(f)$, $B_a(f)$ and C_T are the conductance, susceptance and capacitance of the transducer, respectively [9]:

$$G_a(f) = k^2 \left| \sum_{n=1}^{N} (-1)^n \sqrt{f_n C_n} \sin(\pi f / 2 f_n) e^{-j\omega t_n} \right|^2, \tag{16}$$

$$B_a(f)=\frac{1}{\pi}\int_{-\propto}^{\propto}\frac{G_a(u)}{u-f}du\,, \qquad (17)$$

$$C_T=\sum_{n=1}^{N}C_n=C_{FF}W_0\sum_{n=1}^{N}\frac{W_n}{W_0}\,, \qquad (18)$$

$$f_0=(2\pi)^{-1}(LC_T)^{-1/2}\,, \qquad (19)$$

where C_{FF} is the capacitance per unit length of the electrode pair and N is the number of electrode pairs. The transformer ratio r is determined by the load conductance and $G_a(f_0)$.

Using Fig.4 and neglecting parasitic effects, the efficiency of the transducer $P_{13}(f)$ can be expressed as

$$P_{13}(f)=|T_{13}|^2= \\ =\frac{2\frac{Q_L}{Q_R}\left[G_a(f)/G_a(f_0)\right]}{\left[1+\frac{Q_LG_a(f)}{Q_RG_a(f_0)}\right]^2+\left[Q_L\left(\frac{f}{f_0}-\frac{f_0}{f}\right)+\frac{Q_LB_a(f)}{Q_RG_a(f_0)}\right]^2}\,, \qquad (20)$$

where T_{13} is the transfer function of the transducer and

$$Q_L=2\pi f_0C_Tr^2/G_L\,,Q_R= \\ =2\pi f_0C_T/G_a(f_0)\cong\pi B/4f_0k^2\,. \qquad (21)$$

In order to maximize the efficiency at the passband edges, and to keep the transfer function of the transducer close to the ideal one, the ratio Q_L/Q_R should be small (<<1) and:

$$2\pi BC_{\mathrm{T}}r^2=G_{\mathrm{L}} \qquad (22)$$

Since the apodisation law is known from (18) and (19) the aperture width W_0 and L can be calculated. If the obtained value of W_0 is too high, one should correct it by changing the value of r. In many cases the determination of r and the optimal transducer aperture must be iterative in order to satisfy the conflicting requirements for the amplitude and phase errors, triple transit echo suppression and insertion loss at the edges of the passband. A good starting point for the value of W_0 can be the value given by Butler [12]. For large fractional bandwidths the simple coupling network of Fig.4 should be substituted by a more complex one.

The elements of the matching network of the input transducer are evaluated in the same manner.

The main second-order effect which may degrade the operation of the filter is the acoustic diffraction. It is significant on the ST-quartz substrate if the smallest electrode overlap does not satisfy the inequality

$$W_n^2 f_n\ \ >>\ \ 0.62\,v^2\tau_{\min}\,, \qquad (23)$$

where $\tau_{\min}$ is the minimum time delay of the filter. This inequality is not usually satisfied for long and rather distant transducers. In such a case, additional insertion loss appears:

$$\Delta IL[dB]\approx 10\log_{10}(0.62d\,\lambda_0/W_m^2) \qquad (24)$$

where d is the distance between the center electrodes of the two transducers and W_m the middle value of W_n. The correction for diffraction may be done by additional apodisation which may be determined by solving an integral equation [13] for each electrode in the dispersive transducer. [11]

Software realization of the algorithm

Following the presented algorithm a computer program has been developed. In the first part of the program the data about the waveform (frequency, bandwidth, dispersion, delay, etc.) and transducers (weighting, electrode configuration, load, etc.) are entered. After that, the amplitude and phase responses, and the electrode positions, are computed. Then, the coupling networks are specified and all characteristics checked again, and corrected if necessary. Diffraction compensation is applied, if needed.

Since the standard mask layout programs are not available, the software for this purpose must be specially written. It consists of a set of plotting routines for high precision plotters. The layout is drawn at 100 times the final size. The inaccuracies in step increments and position errors are the source of the amplitude and phase errors or the spurious time sidelobes. The photo reduction equipment is another source of errors. In a typical situation a two step reduction is done. In the first step the accuracy of the calibration over a given area is extremely important since it reduces the maximum size of the artwork. Both types of errors can be overcome to some extent by the use of more complex (and more expensive) equipment, such as an optical pattern generator, or electron beam lithography equipment.

Finally, the artwork on the plotter is done and the data for a more complex mask generation facility are prepared and stored.

Results and discussion

Using the computer program, the compressive filter with the center frequency of 60 MHz, the dispersion of 1μs, and the bandwidth of 10 MHz, has been design and fabricated on quartz. The frequency response of the fabricated filter has been measured. The relative delay characteristic, with respect to the delay at center frequency, is presented in Fig.5. The characteristics shows that the dispersion is about 0.9 μs that satisfies the specification of 1 μs. Insertion loss at center frequency is 36 dB as expected for a quartz substrate. The measured data verify the algorithm presented.

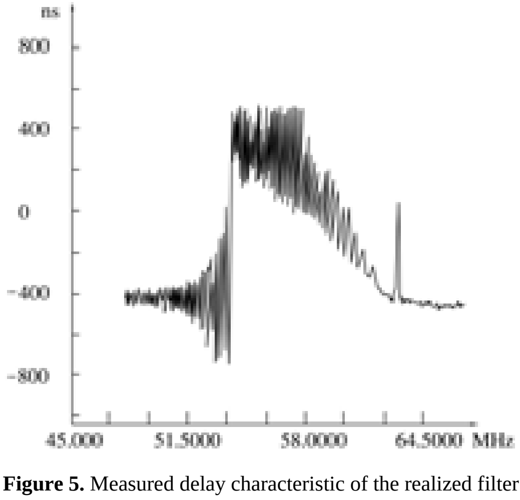

Figure 5. Measured delay characteristic of the realized filter.

The problem of high insertion loss can be resolved by the use of lithium niobate instead of ST-quartz. The lithium niobate substrate can provide the insertion loss around 12 dB.

The algorithm is useful for the design of filters up to 300 MHz and smaller TB-products. With some changes it can be used for the design of the SAW expandor.

Conclusion

The presented algorithm for a complete design of the surface acoustic wave compressor, with one uniform and one dispersive transducer, proved to be efficient for the design of compressive filters with smaller TB-products. The algorithm is complex and it includes specific steps for designing the uniform input transducer, the dispersive output transducer, and the corresponding matching networks. A specific filter has been design with the proposed algorithm and fabricated on quartz. The measured frequency response of the fabricated filter fully meets the specification verifying the correctness and usefulness of the algorithm. The algorithm can be used in the future for the design of optimal filters for the given technology and substrate. Moreover, it can be adapted for the design of SAW expandors.

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Projektovanje kompresora sa površinskim akustičkim talasom sa interdigitalnim pretvaračima

U radu je prikazan algoritam za računarsko projektovanje kompresora sa površinskim akustičkim talasom (PAT) sa iterdigitalnim pretvaračima. Prvo se određuje geometrija uniformnog iterdigitalnog pretvarača (IDP). Pozicije i dužine elektroda (apodizacija) disperzivnog pretvarača se određuju iz impulsnog odziva filtra. Posednji korak u projektovanju je određivanje mreža za prilagođenje između pretvarača i opterećenja i generatora. Ulazni podaci su: centralna učestanost, propusni opseg, disperzija kašnjenja, vrsta podloge, tip kompresora i elektroda, težinska funkcija i otpornosti generatora i potrošača. Izlazni rezultati su geometrija i pozicija elektroda i veličine elemenata mreža za prilagođenje. Algoritam je primenjen u projektovanju filtra centralne učestanosti od 60 MHz i disperzije od 1μs, sa propusnim opsegom od 10 MHz na podlozi od ST kvarca. Izmerena karakteristika kašnjenja napravljenog filtra zadovoljava zadate specifikacije verifikujući tako predloženi algoritam i odgovarajući softver.

Ključne reči: **PAT elementi, PAT filtri, PAT kompresor, ekspandor, projektovanje, algoritam.**

Проектирование компрессора с поверхностной акустической волной с межцифровыми преобразователями

В настоящей работе показан алгоритм для проектирования компрессора с поверхностной акустической волной (ПАВ) с межцифровыми преобразователями при помощи ЭВМ. Впервые определяется геометрия единообразного межцифрового преобразователя (МЦП). Положения и длины электрод (аподисация) рассеивающего МЦП определяются как реакция из побуждающего фильтра. Последний шаг в проектировании - определение сетей для приспосабливания между преобразователем и нагрузкой и источником энергии. Входящие данные – центральная частота, полоса пропускания частот, рассеивание опаздывания, тип подпочвы, тип компрессоров и электрод, весовая функция и устойчивость источников энергии и потребителей. Выходящие результаты – геометрия и положение электрод и размеры элементов

сетей для приспосабливания. Алгоритм служил примером при применении в проектировании фильтра центральной частоты 60 МГц и рассеивания 1 µs с полосой пропускания частот от 10 МГц на подпочве из СТ-кварца. Измеренные характеристики опаздывания проектированого фильтра удовлетворяют заданым срецификациям подтверждая таким образом предложеный алгоритм и соответствующее программное обеспечение.

Ключевые слова: **ПАВ-элемент, ПАВ-фильтр, ПАВ-компрессор, расширитель, проектирование, алгоритм.**

Elaboration du projet pour le compresseur à l'onde superficielle acoustique avec les transducteurs interdigitaux

Ce papier présente l'algorithme pour l'élaboration du projet numérique du compresseur à l'onde superficielle acoustique (PAT) avec les transducteurs interdigitaux.La géométrie du transducteur interdigital uniforme est d'abord déterminée. Les positions et les longueurs des électrodes (apodisation) du transducteur dispersif sont déterminés par la réponse impulsive du filtre. La dernière démarche dans l'élaboration du projet est la détermination des réseaux correspondantes entre le transmetteur et la charge et le générateur. Les données d'entrée sont la fréquence centrale, la portée de mesure, la dispersion du retard, le substratum, le type du compresseur et les électrodes, la fonction du poids et la résistance du générateur. Le résultats de sortie sont la géométrie et la position des électrodes et les valeurs es éléments des réseaux correspondants. L'algorithme est utilisé pour le filtre élaboré de la fréquence centrale de 60 MHz et la dispersion 1µs avec la portée de mesure de 10MHz sur le substratum de ST quartz. La caractéristique mesurée du retard du filtre satisfait les spécifications données vérifiant ainsi l'algorithme proposé et le logiciel correspondant.

Mots clés: **élément PAT, filtre PAT, compresseur PAT, expander, élaboration du projet, algorithme.**