SYNTHESIS OF SAW DEVICES WITH THE DISPERSION IDT AND THE CURVILINEAR CENTER LINE OF ELECTRODES ON THE BASIS OF THE MODIFIED COM METHOD

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In the report the modified COM-equations for designing of a broad class of SAW devices such as filters, resonators, dispersion delay lines are offered. On the basis of the modified equations for coupled modes, the method of synthesis and analysis of SAW devices such as filters and dispersion delay lines using dispersion IDT with curvilinear centerline of electrodes is presented. The results of synthesis of the SAW filter and dispersion delay line are compared to results of experiment.

Keywords: Surface acoustic waves, COM-equations, dispersion delay lines, SAW filters.

At the designing of the wideband dispersion devices on SAW, the IDT with curvilinear centerline of the apertures of electrodes (slanted IDT) usually are used, - ref.1. Usage of a slanted IDT allows to create both the dispersion delay lines (DDL) with a quadratic phase response and the filters which has a linear phase response (fig.3). The method of synthesis of topology of slanted IDT was offered in paper - ref.1. The computational method of frequency characteristics of slanted IDT, on a basis of "physical" model and division of initial topology into channels, was reported in paper - ref.2.

However, offered in ref.1, the approximate equations for synthesis of topology of the SAW device, not always gives adequate results. Besides, the designing of SAW devices on the basis of a physical model not always allows on given topology correctly to calculate frequency characteristics. Therefore on a stage of elaboration there is a necessity to correct topology of IDT after manufacturing of the device. Besides that the physical model does not take into account the influence of such factors as the reflections in a system of IDT electrodes and the triple transit signal.

1. MODIFIED COM – METHOD

Usually used a COM - theory (look, for example, ref.3), based on a deduction and consequent solution of a system of the inhomogeneous differential equations, unfairly complicates the designing of the SAW devices. Within the framework of such theory the account of such factors as a changed period of structure, apodization of electrodes, inhomogeneous distribution of a surface charge on electrodes of IDT is difficult. All listed factors can be simply enough taken into account within the framework of a modified COM method operating a partial cell of structure (one electrode of the IDT or the reflective array).

Let's consider the SAW structure as system of electrodes with alternating polarity and both arbitrary varying period and overlapping of adjacent electrodes. Suppose, that the source of a signal by the amplitude of $\mathbf{U_0}$, is at the left. Consider the k-th electrode of the IDT (fig.1,a). Plane waves $\mathbf{R(Z,\omega)}$ and $\mathbf{S(Z,\omega)}$ are two waves coupled between themselves and propagating in the electrode structure of IDT. Moreover $\mathbf{R(Z,\omega)}$ is propagated in a direction of an axis Z, and $\mathbf{S(Z,\omega)}$ in a direction opposite to an axis Z. Homogeneous plane waves we shall write in the form

$\mathbf{R(Z,\omega)=R(\omega)exp(-j\kappa Z)}$, $\mathbf{S(Z,\omega)=S(\omega)exp(+j\kappa Z)}$,

where $\mathbf{R(\omega)}$, $\mathbf{S(\omega)}$ - the complex amplitudes of the corresponding waves, $\boldsymbol{\kappa}$- wave number.

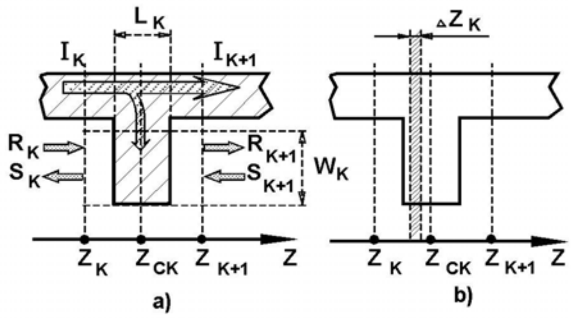

fig.1

A wave $\mathbf{R_K(Z,\omega)}$ is drops on the k-th electrode of the IDT at the left. A wave $\mathbf{S_{K+1}(Z,\omega)}$ is drops on the k-th electrode on the right. Then, for complex amplitudes of past waves, with account for of the mechanisms of reflecting, transition and transformation with factor $\mathbf{\xi_K(\omega)}$ may be written

$$\mathbf{S_K(\omega)=r_K\eta_{1K}exp[-j(\kappa_E-\kappa_O)p_K]R_K(\omega)+ +\eta_{1K}(1-|r_K|^2)^{1/2}exp[-j(\kappa_E-\kappa_O)p_K]S_{K+1}(\omega) + +\xi_K(\omega)\eta_{2K}exp[-j(\kappa_E-\kappa_O)p_K/2]U_O}, \quad (1)$$

$$\mathbf{R_{K+1}(\omega)=\eta_{1K}(1-|r_K|^2)^{1/2}exp[-j(\kappa_E-\kappa_O)p_K]R_K(\omega) + +r_K\eta_{1K}exp[-j(\kappa_E-\kappa_O)p_K]S_{K+1}(\omega)+ +\xi_K(\omega)\eta_{2K}exp[-j(\kappa_E-\kappa_O)p_K/2]U_O}, \quad (2)$$

where $\mathbf{r_K}$ - complex reflectivity from the k-th electrode, $\mathbf{k_E}$ - effective wave number, $\mathbf{\kappa_O=2\pi/\ p_K}$, $\mathbf{p_K=Z_{K+1}-Z_K}$, $\mathbf{\xi_K(\omega)}$ - conversion efficiency of the k-th electrode, $\mathbf{\eta_{1K}=W_{1K}/W_0}$, $\mathbf{\eta_{2K}=W_{2K}/W_0}$, $\mathbf{W_0}$ - maximum aperture, $\mathbf{W_{1K}}$ - overlapping of adjacent electrodes, $\mathbf{W_{2K}=W_0}$ in a case if the false electrodes are used and $\mathbf{W_{2K}=W_{1K}}$ if the false electrodes are not used. The phase multiplicands of reflected (transduced) waves is equal to the phase difference from the center of reflecting (transducing) waves up to the relevant boundaries of cell - $\mathbf{Z_K}$ for $\mathbf{S_K(\omega)}$ and $\mathbf{Z_{K+1}}$ for $\mathbf{R_K(\omega)}$. The center of reflecting (transducing) SAW is accepted in center of an electrode. An effective wave number we shall calculate as $\mathbf{\kappa_E=2\pi/\ \lambda_E=\omega/\ [\ V_O+L_K\ (V_M-V_O\ )\ /p_K]-j\alpha}$, where $\mathbf{V_O}$ – velocity of SAW on a free surface, $\mathbf{V_M}$ – velocity of SAW under a metallized surface, $\boldsymbol{\alpha}$- total losses at the propagation of SAW in electrode structure per unit of length.

The modification of a current in the bus of IDT is caused by the transformation of direct waves, back waves and voltage drops on capacity of an electrode:

$$\mathbf{I_K(\omega)-I_{K+1}(\omega) = \Delta I_K(\omega) = +2\xi_K(\omega)\exp[-j(\kappa_E-\kappa_O)p_K/2]R_K(\omega) + +2\xi_K(\omega)\exp[-j(\kappa_E-\kappa_O)p_K/2]S_K(\omega)+j\omega(C_2/2)U_O.} \quad (3)$$

Now let's consider the members which are responsible for the transformation at passing of the SAW through the electrode of the IDT (fig.1,b). We shall take into account that fact, that the excitation has distributed character. Let's suppose that the direct and the back transformation of SAW on electrodes happen to identical efficiency, i.e. has mutual character.

Let's suppose that the distribution of a surface current on electrodes of IDT **J(Z)** is known and that the mechanism of transformation of SAW by a small site of a surface current $\mathbf{\Delta Z_K}$ of an electrode and all electrode are similar. Then, by summarizing the contributions to the transformation of SAW on a width of an electrode, concerning its center $\mathbf{Z_C}$, and then passing to a limit ($\mathbf{\Delta Z_K \rightarrow 0}$), we shall receive

$$\mathbf{\xi_K = Ga \int_{-L_K/2}^{L_K/2} J(Z)\exp[-j(\omega/V_M-\kappa_O)Z]\,dZ}, \quad (4)$$

where **Ga** – the acoustic radiation conductance on frequency of a synchronism. The calculation of distribution of a surface current on electrodes **J(Z)** in the self-consistent problem or another words with the accounts of the edge effects, final length of IDT and reverse reaction of a piezoelectric can be calculated by a method reported in -ref.4.

The equations (1) - (3) can be rewritten in a matrix form

$$\begin{vmatrix} S_K(\omega) \\ R_{K+1}(\omega) \\ \Delta I_K(\omega) \end{vmatrix} = \begin{vmatrix} P(1,1) & P(1,2) & P(1,3) \\ P(2,2) & P(2,2) & P(2,3) \\ P(3,1) & P(3,2) & P(3,3) \end{vmatrix} \begin{vmatrix} R_K(\omega) \\ S_{K+1}(\omega) \\ U_O \end{vmatrix} \quad (5)$$

Then, P-matrix of the IDT is as a whole defined by a series multiplication of P-matrixes describing each electrode. The using of the equations (1) - (3) with the arbitrary coefficients $\mathbf{\xi_K(\omega)}$ and $\mathbf{\eta_{1K}}$ which are writing for two SAW-structures connected in series the components of total P-matrix may be received.

The presented modified COM method allows to calculate an input admittance of IDT in structure of the filter or resonator with an arbitrary varying period and aperture of electrodes of IDT and real distribution of a surface current on the electrodes of IDT.

2.SYNTHESIS OF SAW DEVICES WITH SLANTED IDT.

Let’s it is necessary to design a SAW device with a slanted IDT having amplitude response in the form of a scaling down or scaling up at the magnification of frequency. A problem of synthesis of topology of the slanted IDT we shall decide by the method similar stated in ref.1. In this case the power, emitted by the IDT in a required frequency band should follow by the expression

$$\mathbf{U_O^2 G_A(f)=P_O K_O(f)}, \quad \mathbf{(6)}$$

where $\mathbf{G_A}$ **(f)** – conductivity of IDT, $\mathbf{P_O}$ - power, emitted by IDT on a center frequency f_o, $\mathbf{K_O(f)=1+K_H[f-f_o]/\Delta f}$, $\mathbf{U_O=const(f)}$ - signal amplitude on an input IDT, $\mathbf{K_H= const(f)}$ - factor of inclination of a frequency response. For a scaling down of insertion losses in a high-frequency region $\mathbf{K_H > 0}$, and for linear growth of insertion losses in a high-frequency region $\mathbf{K_H < 0.}$ Carrying out the transformations similar to those that has been executed in ref.1, for frequency dependence of the aperture of IDT, we shall receive

$$\mathbf{W(f) = W(f_o)[f_o/f]K_O(f)\{[(R_G)^2+ +X^2(f)]/[(R_G)^2+X^2(f_o)]\}^{1/2}}, \quad \mathbf{(7)}$$

where **W(fo)** - aperture of IDT on a center frequency selected from a condition of absence of a diffraction and a permissible level of insertion losses, $\mathbf{R_G}$ - resistance of the generator, **X(f)** – imaginary part of IDT impedance.

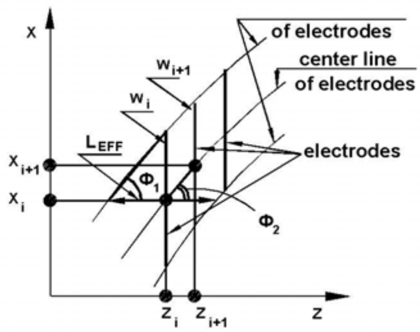

fig.2

The position of centerline of the apertures of IDT electrodes we shall define from a condition of constant of IDT length in a transverse direction for each **X**-coordinate: $\mathbf{L_{EFF}(X)\approx N_{EFF}(f)\lambda/2=const,}$ $\mathbf{N_{EFF}(f)=f[T/\Delta f]^{1/2}}$ -ref.1, where **T** - dispersion delay in IDT, **Δf** - bandwidth of IDT. From consideration of a fig.2 it is possible to write expressions:

$$\mathbf{tg\,\phi_1 = W_i/L_{EFF}}, \quad \mathbf{(8)}$$

$$\mathbf{tg\,\phi_2 = \Delta X_i/\Delta Z_i}, \quad \mathbf{(9)}$$

where $\mathbf{\Delta X_i = X_{i+1} - X_i}$, $\mathbf{\Delta Z_i = Z_{i+1} - Z_i}$ - distance on **X** and **Z** axes between the coordinates of centers of i-th and i+1- th of IDT electrodes, $\mathbf{W_i}$ - aperture of an i-th electrode, $\mathbf{\phi_1,\phi_2}$ - angles of inclination of boundary of the apertures and centerline of electrodes respectively, concerning an axes **Z** (fig. 2). In case of a slow varying of the aperture of IDT $\mathbf{(W_{i+1} - W_i)/W_{i+1} << 1}$, curvature of a line of centers of electrodes slowly varies also. In this case $\mathbf{\phi_1 \approx \phi_2}$. Then, from eq.(3) and eq.(4) it is possible to receive $\mathbf{\Delta X_i \approx \Delta Z_i\ W_i / L_{EFF}}$ and $\mathbf{X_{i+1} = X_i + \Delta X_i}$ и $\mathbf{X_1 = 0,}$ **Z** -coordinates of electrodes are determined by a standard manner.

3. ANALYSIS OF SAW DEVICES WITH SLANTED IDT

Let's consider the SAW device with dispersion IDT and curvilinear centerline of electrodes (fig. 3). Calculation of IDT matrix of conductivity we shall perform on the basis of modified COM method and the method of division of initial SAW structure on channels.

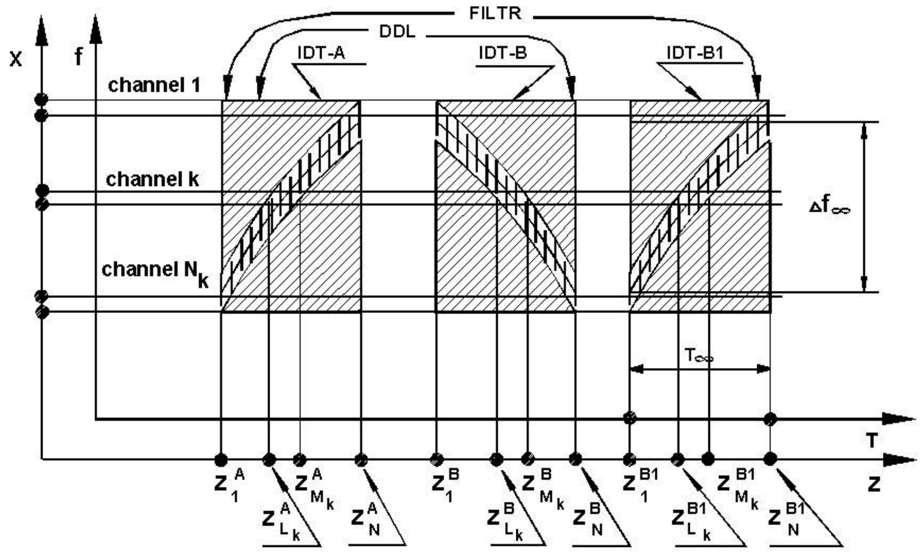

Fig.3.

Components of an input admittance of IDT we shall define as the sum of partial conductivities of all channels

$$\mathbf{Y(l_Y,m_Y)=\sum_{k=1}^{N_K} Y_K(l_Y,m_Y)}, \qquad \mathbf{(10)}$$

where $\mathbf{N_K}$ - number of channels, $\mathbf{Y_K}$ $\mathbf{(l_Y,\ m_Y)}$ - component of a matrix of an input admittance in the k-th channel, $\mathbf{l_Y}$=1,2, $\mathbf{m_Y}$=1,2. Number of channels, into which the structure is divided, should be taken enough, that the results of calculation of frequency characteristics do not vary at increasing of $\mathbf{N_K}$. The contribution of the k-th channel $\mathbf{Y_K(l_Y,m_Y)}$ in the total conductivity of the SAW device we shall define, considering the k-th channel as the independent SAW device, and using the components of P-matrixes of the input IDT-A $\mathbf{P^{(A)}_K(l_P,m_P)}$ and the output IDT-B $\mathbf{P^{(B)}_K(l_P,m_P)}$ in the k-th channel. Then, for an input admittance of the k-th channel we shall receive

$$\mathbf{Y_K(1,1)=P^{(A)}_K(3,3)+ +P^{(B)}_K(1,1)P^{(A)}_K(3,2)P^{(A)}_K(2,3)/Y_{KO}}, \qquad \mathbf{(11)}$$

$$\mathbf{Y_K(1,2)=P^{(A)}_K(3,2)P^{(B)}_K(1,3)\Phi_K/Y_{KO}}, \qquad \mathbf{(12)}$$

$$\mathbf{Y_K(2,1)=P^{(A)}_K(2,3)P^{(B)}_K(3,1)\Phi_K/Y_{KO}}, \qquad \mathbf{(13)}$$

$$\mathbf{Y_K(2,2)=P^{(B)}_K(3,3)+ +P^{(A)}_K(2,2)P^{(B)}_K(1,3)P^{(B)}_K(3,1)/Y_{KO}}, \qquad \mathbf{(14)}$$

where $\mathbf{Y_{KO}= (\Phi_K)^2 - P^{(A)}_K(2,2)\ P^{(B)}_K(1,1)}$,
$\mathbf{\Phi_K = EXP(\ j\ 2\pi\ Z^{(AB)}_K / \lambda - \alpha\ Z^{(AB)}_K)}$, $\mathbf{Z^{(AB)}_K = Z^{(B)}_1 - Z^{(A)}_N}$ –distance between the first electrode IDT-B and last electrode IDT-A (fig. 3), λ - wavelength on a free surface.

The calculation of components $\mathbf{P^{(A)}_K(l_P,m_P)}$ and $\mathbf{P^{(B)}_K(l_P,m_P)}$ is perform on the basis of a modified COM method. In order to synchronize the channels among themselves it is necessary to take into account the initial phase for the first electrode of each channel IDT-A (IDT-B). For this purpose in the components of a P-matrix of a equation (5) we shall add the phase factors for the first electrodes of each channel:

$$\mathbf{P^{(A)}(1,1) = P\ (1,1)\ [\ F^{(A)}_1\ \{Z^{(A)}_{K,1}\}]^2}, \qquad \mathbf{(15)}$$

$$\mathbf{P^{(A)}(1,2) = P\ (1,2)\ F^{(A)}_1\{Z^{(A)}_{K,1}\}}, \qquad \mathbf{(16)}$$

$$\mathbf{P^{(A)}(1,3) = P\ (1,3)\ F^{(A)}_1\{Z^{(A)}_{K,1}\}}, \qquad \mathbf{(17)}$$

$$\mathbf{P^{(A)}(2,1) = P^{(A)}(1,2)}, \qquad \mathbf{(18)}$$

$$\mathbf{P^{(A)}(3,1) = P\ (3,1)\ F^{(A)}_1\{Z^{(A)}_{K,1}\}}, \qquad \mathbf{(19)}$$

where $\mathbf{F^{(A)}_1\ \{Z^{(A)}_{K,1}\} = EXP\ (\ j\ 2\pi\ Z^{(A)}_{K,1} / \lambda_M - \alpha\ Z^{(A)}_{K,1}\ )}$, $\mathbf{Z^{(A)}_{K,1} = Z^{(A)}_{Lk} - Z^{(A)}_1}$ – distance between the first electrode in the k-th channel of IDT-A (with number L_K) and the first electrode of all IDT-A, $\mathbf{\lambda_M}$ - wavelength under a metallized surface (contact bus). The other components of a P-matrix for the first electrode remain without a changing.

For the last electrodes of each channel IDT-A the components of a **P**-matrix with account of the phase factor will be:

$$\mathbf{P^{(A)}(1,2) = P(1,2)\ F^{(A)}_2\{Z^{(A)}_{K,2}\}}, \qquad \mathbf{(20)}$$

$$\mathbf{P^{(A)}(2,1) = P^{(A)}\ (1,2)}, \qquad \mathbf{(21)}$$

$$\mathbf{P^{(A)}(2,2) = P(2,2)\ [\ F^{(A)}_2\{Z^{(A)}_{K,2}\}]^2}, \qquad \mathbf{(22)}$$

$$\mathbf{P^{(A)}(2,3) = P(2,3)\ F^{(A)}_2\{Z^{(A)}_{K,2}\}}, \qquad \mathbf{(23)}$$

$$\mathbf{P^{(A)}(3,2) = P(3,2)\ F^{(A)}_2\{Z^{(A)}_{K,2}\}}, \qquad \mathbf{(24)}$$

where $\mathbf{F^{(A)}_2(Z^{(A)}_{K,2}) = EXP\ (\ j2\pi Z^{(A)}_{K,2}/\lambda_M - \alpha\ Z^{(A)}_{K,2})}$, $\mathbf{Z^{(A)}_{K,2}=Z^{(A)}_N - Z^{(A)}_{Mk}}$ – distance between the last electrode of all IDT (with number **N**) and last electrode in the k-th channel ($\mathbf{M_K}$). The other components of a P-matrix for the last electrode remain without a changing.

The similar expressions can be written for IDT-B with components $\mathbf{P^{(B)}_K(l,m)}$, and condition $\mathbf{F^{(B)}_2(Z^{(B)}_{K,2})=1}$, because a phase change of a wave outside IDT-B unessentially. Now the components of a **P**-matrix of the k-th channel $\mathbf{P^{(A)}_K(l_P,m_P)}$ and $\mathbf{P^{(B)}_K(l_P,m_P)}$ can be calculated by a multiplication of the relevant components for the electrodes in each channel

$$\mathbf{P^{(A,B)}_K(l_P,m_P) = \prod_{n=L^{A,B}_K}^{M^{A,B}_K} F\{P^{(A,B)}_{Kn}(l,m)\}}, \qquad \mathbf{(25)}$$

where $\mathbf{L_K}$, $\mathbf{M_K}$ - the numbers of the first and last of the electrodes in each channel. The product in eq.(25) should be understood as a calculation of the series products defined by the equations analogies to eq.(1) - (3), but which are written for the two adjacent electrodes.

4. THE RESALTS OF DESIGNING OF THE FILTER AND DDL WITH DISPERSION SLANTED IDT.

The filter with the dispersion IDT and parameters: f_O= 105 **MHz**, **Δf**=10 **MHz**, K_C=1.45 was designed by the offered method, and then is made on a substrate of **$LiNbO_3$ Y, Z**-cut, size by 13x3.5mm^2. For the necessary squareness of the frequency response of the filter on the basis of the procedure of synthesis was established

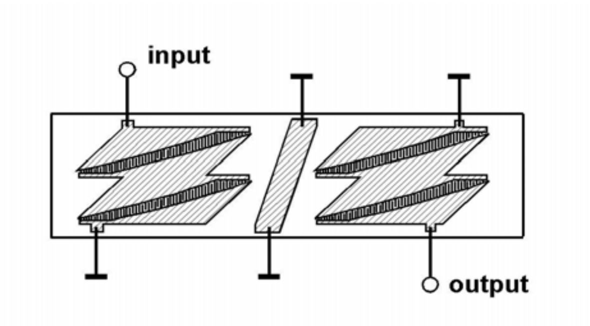

Fig.4 Topology of the filter

that, the dispersion delay in the each IDT should be equal to 1.9 **μs** at Δf_∞=15 MHz and K_H=0.3. The aperture of electrodes on a center frequency **W(fo)** should be equal to 11 Σ_0. Each of the IDT should include 403 split of the electrodes. The topology of the filter is presented in fig.4. The measured frequency characteristics of the filter are presented in fig. 5a, and the results of

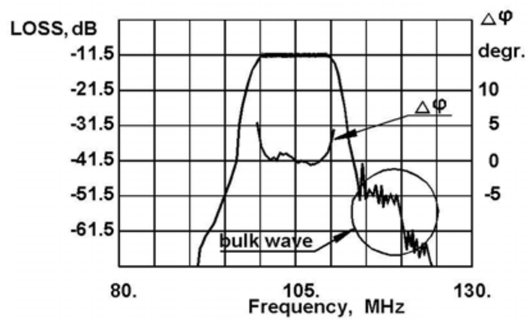

fig.5,a. Measured responses of the filter.

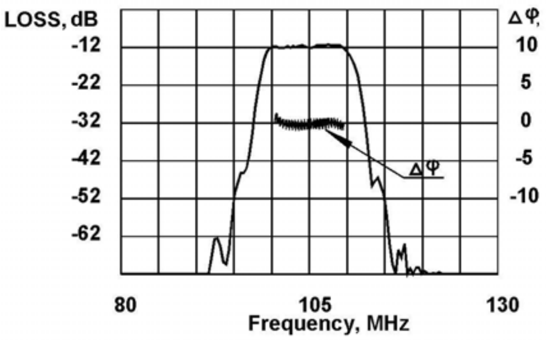

Fig.5,b. Calculated responses of the filter.

calculations by a modified COM method are presented in fig.5b. The phase characteristic of the filter **Φ(f)** is presented by the deviations from the linear law: $\Delta\Phi = \Phi(f) - 2\pi T_0 (f_o - f)$, where T_0 =2.3179 **μs** is delay on the frequency **fo.**

By the offered method the dispersion delay lines were designed, and then are made on substrates of **$LiNbO_3$ Y,Z**-cut. Up-chirp (without apodization) and down-chirp (with Taylor weighting) has the parameters: f_O = 700**MHz**, **Δf** =200 **MHz**, **T=0.6 μs**. With the using of the procedure of the synthesis has been established that the flat response of the up-chirp take place if K_H =0, Δf_∞=260 **MHz** and T_∞=0.34 **μs** for every IDT, **W(fo)=25Σ_0.** Each of the slanted IDT includes 549 of electrodes. The frequency responses of up-chirp and down-chirp are presented in fig.6 and fig.7 respectively. The calculated and measured values of the minimum insertion losses were -18.2 dB and -22 dB respectively.

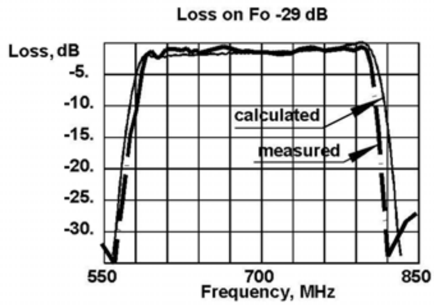

Fig.6. Frequency responses of the up-chirp

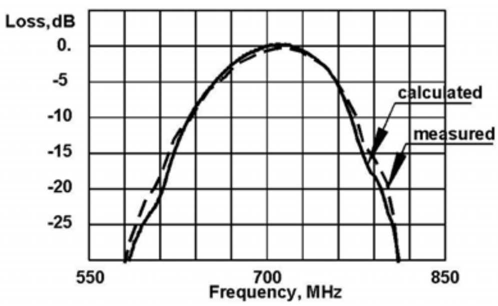

Fig.7. Frequency responses of the down-chirp

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