Scanning window technique in SPUDT optimization

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Abstract – This paper is devoted to optimization of single-phase unidirectional transducers (SPUDT). The essence of the suggested algorithm is a consideration of all possible electrode combinations inside a local region that scans step by step throughout optimized transducers. The algorithm can keep control of filter parameters according to any desired priority scheme, i.e. provides a desired compromise between insertion loss, triple transit suppression, stopband rejection, in-band ripple, etc. Our EWC/SPUDT analysis is based on T-matrix approach [1].

I. INTRODUCTION

Because of much more complicated relationship between SPUDT topology and its frequency characteristics compared with bi-directional transducers, up to now there is no generally accepted technique for SPUDT optimization. Few publications describing in details optimization procedures for SPUDTs are based on coupled-mode analysis and optimization of continuous distribution of SAW sources and reflectors. Unfortunately, their following discretization disturbs transducer characteristics in case of wide passbands.

Here we suggest a method that performs optimization of discrete electrode structure directly.

II. IDT STRUCTURES

In this paper we deal with Electrode Width Controlled (EWC) SPUDTs [2]. For strong piezoelectric substrates like lithium niobate we use, as in [2], reflective electrodes of the width $\lambda/4$ ($\lambda$ is wavelength) (Fig.1a) [2]. However for ST-quartz and thick metallization, $3\lambda/8$ reflective electrodes (Fig.1b) provide higher reflection [3].

![Fig.1. EWC / SPUDT structures with different widths of reflective electrodes: $\lambda/4$ (a) and $3\lambda/8$ (b)](image)

For mounting of IDTs we use basic cells of fifteen types (Fig.2). Each cell is one wavelength long and includes no more than 1 “hot” and 2-4 grounded electrodes of different widths. Cells may be active or passive, they may include reflectors or not. Positions of SAW sources and reflectors are different in different cells. Each IDT is a combination of these cells. The only restriction on such combination is: immediate neighborhood of “hot” electrodes of adjacent cells is prohibited to reduce their mutual influence.

![Fig.2. Basic cells for SPUDT mounting](image)

We also consider SPUDTs having several acoustic channels with different IDT periodicities – quasi-slanted SPUDTs (Fig.3).

![Fig.3. Quasi-slanted SPUDT with 3 acoustic channels](image)

III. SPUDT SIMULATION

In our filter design process, SPUDT simulation is based on Reflective Array Model (RAM) [1]. We use RAM with a modified transmission T-matrix. This $T(3*3)$-matrix relates waves and currents on the right-hand and left-hand sides of an electrode or electrode group (Fig.4a):

\[
\begin{bmatrix}
    b_{n+1} \\
    c_{n+1} \\
    I_{n+1}
\end{bmatrix} =
\begin{bmatrix}
    T_{k1} & b_n & c_n \\
    I_{n+1} & 0 & I_n
\end{bmatrix},
\]

(k,l=1,…,3)

where $c_n$ and $b_{n+1}$ are incident waves, $b_n$ and $c_{n+1}$ are output waves; $(I_{n+1} - I_n)$ is the current entering electrodes of $(n+1)$-th cell. Cascading $T$-matrixes of all $N$ cells gives $T$-matrix of the
whole IDT, which relates SAWs on the IDT (Fig. 4b) and total short-circuited current:

$$\begin{bmatrix}
n_N \\ c_N \\ I_N
\end{bmatrix} = \left[T_{kl}\right]_{IDT} \cdot \begin{bmatrix}
I_0 \\ c_0 \\ b_0
\end{bmatrix}, \quad (k, l = 1, \ldots, 3)$$

**Fig. 4.** Forward ($c_n$) and backward ($b_n$) SAWs on: a) the ($n+1$)-th basic cell; b) the whole IDT with $N$ cells

Using $T$-matrix, one can calculate $P$- and $S$-matrices and then IDT frequency characteristics [1,2]. Assuming $c_0 = 0$ (no incident SAW from the left of the IDT) and $b_0 = 1$, we have $P_{22} = c_N / b_N$, $P_{21} = 1 / b_N$, $P_{32} = s / b_N$, $P_{33} = -P_{32} / 2$. By changing the direction of $T$-matrix cascading one can obtain $P_{11}, P_{21}, P_{31}, P_{33}$.

To compute the components of $T$-matrices for various electrode groups, we preliminary computed a modified transfer matrix for a single electrode:

$$\begin{bmatrix}
  b_n \\ c_n \\ I_n
\end{bmatrix} = \begin{bmatrix}
  \gamma \theta / t & -r / t & 0 \\ r / t & \gamma \theta / t & 0 \\ -1 / 2 \left(\gamma + \gamma / \theta + \gamma / \theta / t\right) & -1 / 2 \left(\gamma + \gamma / \theta / t\right) & 1
\end{bmatrix} \begin{bmatrix}
  b_0 \\ c_0 \\ I_0
\end{bmatrix},$$

where

$$\gamma = j \sqrt{\omega W G_i / 2} \sigma(k_0); \quad \gamma' = j \sqrt{\omega W G_i / 2} \sigma(-k_0);$$

$$\sigma(k_0) = \frac{1}{a_i / 2} \int_{-a_i / 2}^{a_i / 2} \sigma(x) e^{jk_0 x} dx; \quad G_i = \frac{1}{\varepsilon_{\infty}} \frac{V_{\text{free}}}{V_{\text{shorted}}};$$

$r$ and $t$ are the reflection and transmission coefficients per one electrode (referred to its center, computed by FEM/BEM method); $\theta = k_0 p$; $p$ is the length of a cell (in our case $p$ equals one wavelength); $k_0$ is the SAWs wave number in a cell; $W$ is the beam aperture; $G_i$ is the piezoelectric coupling parameter of wave; $\omega$ is the angular frequency; $\varepsilon_{\infty}$ is the dielectric constant, $V_{\text{free}}$ and $V_{\text{shorted}}$ are the wave velocities for free and shorted crystal surfaces; $\sigma(k_0)$ is the Fourier transform of the charge density which is computed for a periodic infinite array of cells. The current entering an electrode is

$$I = -j \omega W \sigma(k_0) \phi_i [1],$$

where $\phi_i$ is the mean potential of the incident and leaving waves taken at the electrode center. Cascading the transmission matrices of single electrodes one can obtain a transmission matrix for any basic cell (Fig. 2), for a group of cells, and for the whole IDT.

Knowing $P$-matrixes, one can obtain the $Y$-matrix of a one-channel SPUDT filter [4]:

$$Y_{22} = \frac{\hat{P}_{33} \hat{P}_{23} e^{-j k L}}{I - \hat{P}_{11} P_{22} e^{-2 j k L}}, \quad Y_{21} = \frac{\hat{P}_{33} \hat{P}_{23} e^{-j k L}}{I - \hat{P}_{11} P_{22} e^{-2 j k L}},$$

$$Y_{11} = P_{33} + \frac{\hat{P}_{33} \hat{P}_{23} e^{-j k L}}{I - \hat{P}_{11} P_{22} e^{-2 j k L}}, \quad Y_{12} = \frac{\hat{P}_{33} \hat{P}_{23} e^{-j k L}}{I - \hat{P}_{11} P_{22} e^{-2 j k L}},$$

where $L$ is the distance between the transducers, $P_{ij}$ are the components of $P$-matrix for the 1-st IDT and $\hat{P}_{ij}$ for the 2-nd one. In case of multi-channel (quasi-slanted) IDTs (Fig. 3) $Y$-matrixes of individual channels are summarized with accounting individual distances $L_m$ between transducers in each channel.

For acceleration of our design process, $T$-matrixes of all basic cell types (Fig 2) have been computed beforehand. In this case the mutual influence of cells is assumed to be small, so the charge distribution in each basic cell is calculated assuming the cell to be surrounded by cells of the same type.

Finally, for more accurate simulation of adjusted SPUDTs, the charge distribution on electrodes is computed considering final positions and widths of all electrodes. In this case mutual influence of cells is taken into account.

This technique is applicable to different substrates and IDT structures with a wide range of piezoelectric coupling strength and SAW reflectivity level.

**IV. SPUDT DESIGN APPROACH**

Unlike most publications, our algorithm optimizes not continuous distributions of SAW sources and reflectors but discrete ones directly.

**Fig. 5.** Scanning “window” in SPUDT optimization

Similar to [5], the main idea of our optimization procedure is variation of IDT structure at each step only in a local region, “window” (Fig. 5). However, unlike [5], in SPUDTs we vary not the polarity of an individual electrode but the number (type) of a basic cell (Fig. 2). The algorithm considers all combinations of the used basic cells inside the “window” while the IDT structure outside this region is permanent until the “window” changes its position (Fig. 5). The “window” scans step by step throughout the input and output IDTs many times whilst any improvement of its characteristics takes
As mentioned above, we exclude situations when “hot” electrodes of adjacent cells are neighbors because in this case the mutual influence of cells is very large. Moreover, we usually use only the cells of numbers 6-15 (Fig.2) for the input (left) IDT and the cells of numbers 1-5 and 11-15 for the output (right) IDT. The “window” size should be rather short (3-5 cells) because of a large amount of different cell combinations inside the “window” when all mentioned cells are used in the design process. However, initially IDTs without reflections are optimized to be starting structures for the following SPUDT design, i.e. only cells of numbers 6, 9, 11 are used for the left IDT and of numbers 1, 4, 11 for the right one, so much longer “window” (8-10 cells) is acceptable here.

Inasmuch as a huge amount of different SPUDT modifications should be considered, the problem of time expense for each IDT modification analysis becomes very topical. T-matrix approach allows dividing IDT into desired parts and calculating T-matrixes of these parts separately with their following cascading to derive the whole IDT matrix. This is important for our algorithm acceleration: at each step the algorithm recalculates, as a rule, only a small part of the IDT (inside the “window”) while T-matrixes of other IDT parts are calculated only once at each “window” position. Moreover, most of structures are rejected after analysis of filter response at a few frequency points.

The flowchart of our software for a SPUDT filter design is shown in Fig.6. After 1st IDT optimization the IDTs are interchanged and the process is repeated.

The filter frequency response (FR) is analyzed step by step in different frequency regions:
- in the passband, where in-band ripple, insertion loss, triple-transit signal, bandwidth, and phase characteristic must be not worse than in specifications;
- in far-out regions, where FR side-lobes must be not higher than in specifications;
- in most important stopband regions, where ultimate rejection should be as large as possible, i.e. better than in all previous filter modifications.

At each step, IDT analysis will be interrupted instantly unless at any frequency the filter response meets above demands. As a result, 100-1000 IDT modifications per second are considered on a personal computer. Successful combination of neighbor cells provides not only a good SAW source distribution but also resonant acoustic regions like in [3], which reduces IDT dimension. In some cases the algorithm provides a SPUDT dimension about twice shorter compared with bi-directional IDTs having similar frequency responses.
Two examples of designed SPUDT filters are presented in Figs. 7, 8.

**Fig. 7.** 1-channel SPUDT filter; bandwidth of 3%; 101*101 cells in IDTs; YZ-LiNbO3;  
1 – designed frequency response;  
2 – simulation with accounting mutual cells influence

**Fig. 8.** 1-channel SPUDT filter; bandwidth of 1%; 121*121 cells in IDTs; ST-quartz;  
1 – designed frequency response;  
2 – simulation with accounting mutual cells influence

Multi-channel (quasi-slanted) SPUDTs give additional resources for obtaining wide bandwidth and special FR forms due to additional parameters for optimizations: periodicities and apertures of individual channel. Fig. 9 shows an example of designed quasi-slanted SPUDT filter with three acoustic channels.

**Fig. 9.** 3-channel SPUDT filter; bandwidth of 5%; 91*73 cells in IDTs; YZ-LiNbO3;  
1 – designed frequency response;  
2 – simulation with accounting mutual cells influence

VI. CONCLUSION

Using the scanning “window” method, the original optimization algorithm is developed for EWS SPUDTs. This technique is applicable to different substrates and IDT structures with a wide range of piezoelectric coupling strength and SAW reflectivity level, to one-channel filters and multi-channel (quasi-slanted) IDTs.

REFERENCES


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