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Computer aided design of disperssive delay lines

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Abstract: Surface acoustic wave (SAW) dispersive delay lines (DDLs) are used to generate and compress frequency modulated chirp signals. The simplest DDL consists of two interdigital transducers placed on the piezoelectric substrate. The interdigital transducers convert the electric signal to surface acoustic wave and vice-versa. The frequency response of the DDL depends on the shape of the transducers. Because of so called second order effects analysis and design of dispersive delay lines is very complicated. The final result depends on the precision of mathematical model of the device.

Key-Words: surface acoustic waves, dispersive delay lines, signal compression

1 Introduction

Surface acoustic wave (SAW) dispersive delay lines (DDL) are used as signal generators and compressors for instance in radiolocation [1]. Some kind of dispersive structures are used in SAW wireless sensors to improve the sensor sensitivity and operating range [2]. In these applications linear frequency modulated signals are used most commonly fig 1. The main parameters of the signal are: center frequency f_0, bandwidth B and duration time called also dispersion time T.

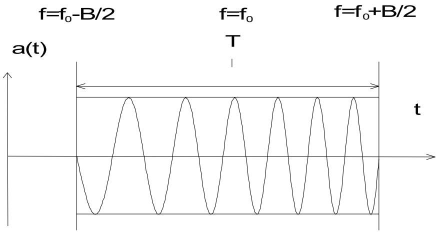

Fig. 1. Linear frequency modulated chirp signal.

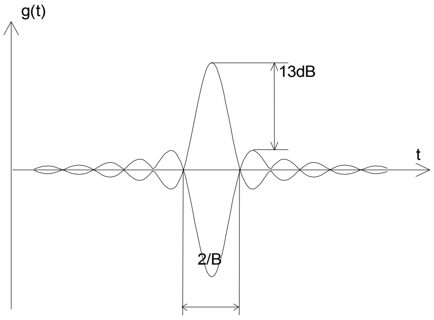

Fig. 2. Compressed signal.

The shape of frequency response of the signal depends on the BT product. For large BT products (over 100) the frequency response is almost rectangular. To compress the signal DDL with reversed time response must be used. In this case the compressed signal with narrow mainlobe and –13dB sidelobes is obtained (fig. 2). To reduce the sidelobes some amplitude weighting of the compressor, for instance Hamming weighting may be implemented. It allows to lower the sidelobes level below -42dB.

2 Dispersive delay line modeling

Dispersive delay line consists of two interdigital transducers (IDT) placed on the piezoelectric surface (fig. 3). The interdigital transducer converts electric signal into surface acoustic wave and vice-versa. The frequency response depends on the shape of IDTs.

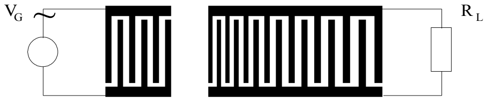

Fig. 3. Surface acoustic wave dispersive delay line.

For the modeling of IDT the simple transversal filter model may be used (fig. 4). In this model the delays $t_1..t_n$ represent distances between electrodes and weighting factors $a_1..a_n$ represent electrode lengths. Using this model the phase characteristic may be changed by changing the distances between electrodes, and the amplitude by weighting the electrode lengths.

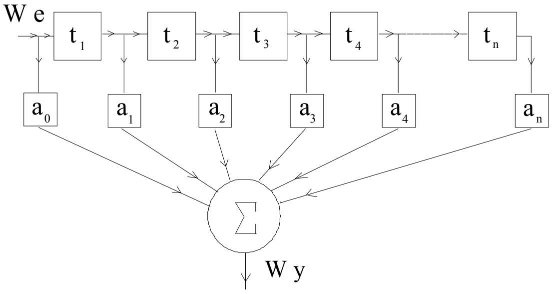

Fig 4. Transversal filter model.

In practice there are many so called second order effects that strongly influence the DDL response. The most important effects are surface acoustic wave diffraction, interdigital reflections and bulk wave. Some of the effects my be significantly reduced by choosing appropriate piezoelectric substrate shape and interdigital transducers configuration. But the other must be taken into account during DDL design. It makes the DDL mathematical model more complicated. In this case the design process must be divided into two stages. In the first stage the DDL is synthesized using the simple transversal filter model. In the second the DDL is analyzed using more complicated model and necessary corrections are made.

3 Dispersive delay lines synthesis

Generally the signal may be described using the complex notation [3]:

$$s(t) = a(t)e^{-j\varphi(t)} \tag{1}$$

The electrodes are positioned that the surface acoustic wave sources occur at times for which the desired chirp waveform is real, that is, at times for which the sample phase is 0 or π.

The sample times t_n are found by solving the equation:

$$\varphi(t_n) = n\pi + \text{const} \tag{2}$$

For a linear chirp filter of bandwidth B dispersion T and center frequency f_0 the desired impulse response is:

$$s(t) = \begin{cases} \exp\left[2\pi j\left(f_0 t + \dfrac{B}{2T}t^2\right)\right] & |t| \le T/2 \\ 0 & |t| > T/2 \end{cases} \tag{3}$$

The total number of electrodes:

$$N = 2f_0T + 1 \tag{4}$$

As a result electrodes positions x_n can be calculated:

$$x_n = v_{eff} f_0 \frac{\Delta\tau}{B}\left[-1 + \left(1 - \frac{1}{f_0^2}\frac{B}{T}\left(\frac{N}{2} - n\right)\right)^2\right] \tag{5}$$

where v_{eff} is effective velocity of surface acoustic wave.

In order to obtain flat impulse response the electrodes lengths must be weighted using the formula:

$$\frac{a_n}{A} = \left[\frac{f_n}{F}\right]^{-3/2} \tag{6}$$

where:
a_n – n-th electrode overlap,
A – transducer aperture,
f_n – instantaneous frequence,
F – normalization constant.

4 Dispersive delay lines analysis

For the dispersive delay lines analysis the quasi static interdigital transducer model [4] was used. The model was developed for SAW bandpass filters [5]. In this model the interdigital transducer is treated as a set of linear surface acoustic wave sources placed between each pair of electrodes.

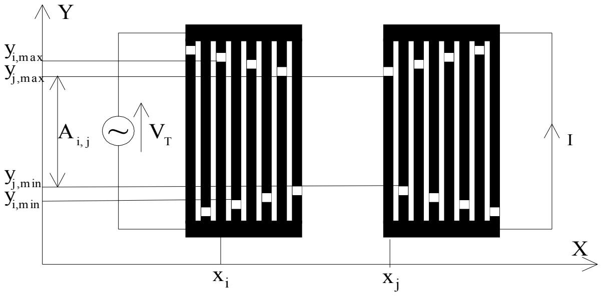

Fig. 5. Topology of analyzed structure.

The DDL transadmitance can be calculated using the formula (upper index denotes number of transducer):

$$Y_{21} = -\omega\Gamma_s\overline{\sigma}_g^{(1)}(k_p)\overline{\sigma}_g^{(2)}(k_p)\sum_{i=1}^{N^{(1)}-1}\sum_{j=1}^{N^{(2)}-1}A_{i,j}e^{-jk_p(x_j - x_i)} \tag{7}$$

where:

$$\overline{\sigma}_g = -j\varepsilon_s(\infty)\frac{(-1)^m}{P_{-s}(-\cos\Delta)}P_m(\cos\Delta) \tag{8}$$

$$\Gamma_s = \frac{1}{\varepsilon_s(\infty)}\cdot\frac{\Delta v}{v_0}\left(1 + \frac{3}{2}\cdot\frac{\Delta v}{v_0}\right) \tag{9}$$

$$k_p = \left[k_m^2 + \frac{k_m^2 - k_0^2}{2}\left(1 + \frac{P_s(-\cos\Delta)}{P_{-s}(-\cos\Delta)}\right)\right]^{\frac{1}{2}} \quad (10)$$

$$\omega = 2\pi f \quad (11)$$

$$\varepsilon_s(\infty) = \varepsilon_0 + \varepsilon_p^T \quad (12)$$

$$\Delta = \frac{\pi a}{p} \quad (13)$$

ω – pulsation,

f – frequency,

Γ_s – constant depending on the piezoelectric substrate,

$\overline{\sigma}_g(k_p)$ – Fourier transform of surface charge density,

k_p – wavenumber,

N – number of electrodes,

x – electrode position,

y – electrode gap position,

$A_{i,j}$ – acoustic channel width,

a – electrodes width,

p – transducer period,

P_m – Legendre polynomial,

P_{-s} – Legendre function,

s – fractional part of $(kp/2\pi)$,

ε_p^T - effective dielectric constant,

V_0 – surface acoustic wave velocity.

To include the diffraction effect parabolic simplification may be used. It assumes that the SAW velocity depends on the propagation angle θ according to the formula:

$$\frac{v(\theta)}{v_0} = 1 + \frac{\gamma}{2}\theta^2 \quad (14)$$

γ – surface acoustic wave anisotropy factor.
Using the model, the equation (7) may by expressed as:

$$Y_{21} = -\frac{\sqrt{2}}{2}\omega\Gamma_s\overline{\sigma}_g^{(1)}(k_0)\overline{\sigma}_g^{(2)}(k_0)e^{j\frac{\pi}{4}\operatorname{sgn}(1+\gamma)} \cdot \quad (15)$$

$$\sum_{i=1}^{N^{(1)}-1}\sum_{j=1}^{N^{(2)}-1} q_{ij}e^{-jk_0x_{ij}}\left[H(A_{ij},1+\gamma) + H(D_{ij},1+\gamma) - H(E_{ij},1+\gamma) - H(F_{ij},1+\gamma)\right]$$

where:

$$q_{ij} = \sqrt{\frac{\pi x_{ij}|1+\gamma|}{k_0}} \quad (16)$$

$$A_{ij} = \frac{y_{j+1}^{(2)} - y_i^{(1)}}{q_{ij}} \qquad D_{ij} = \frac{y_j^{(2)} - y_{i+1}^{(1)}}{q_{ij}} \quad (17)$$

$$E_{ij} = \frac{y_{j+1}^{(2)} - y_{i+1}^{(1)}}{q_{ij}} \qquad F_{ij} = \frac{y_j^{(2)} - y_i^{(1)}}{q_{ij}} \quad (18)$$

$$H(x,d) = xE(x,d) + \frac{1}{\pi}e^{-j\frac{\pi}{2}\operatorname{sgn}(d)(x^2+1)} \quad (19)$$

$$E(x,d) = C(x) - j\operatorname{sgn}(d)S(x) \quad (20)$$

C(x), S(x) – Fresnel integrals.
The integral may be evaluated using numerical methods.

5 Practical results

According to the model various types of dispersive delay lines may by designed and analyzed. As an example the results of dispersive delay line with the following parameters will be presented:

center frequency – 70MHz,
bandwidth – 6Mhz,
dispersion – 10µs.

The compressed signal width is 220ns at -6dB. To reduce the sidelobes Hamming weighting of compressor was implemented. Theoretical frequency responses of the expander and compressor are presented in fig. 6 and 7. Compressed signal is presented in fig. 8.

The DDLs were manufactured on quartz substrate. The practical results are presented in fig. 9-11. The frequency responses of expander and compressor were made made using network analyzer. The compressed signal was calculated as reverse Fourier transform of expander and compressor frequency responses product.

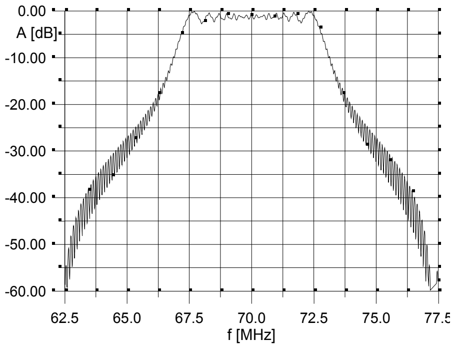

Fig. 6. Theoretical characteristic of expander.

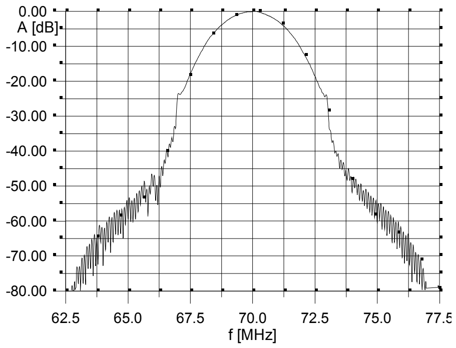

Fig. 7. Theoretical characteristic of compressor.

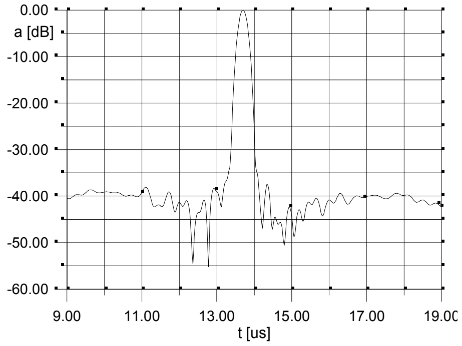

Fig. 8. Compressed signal.

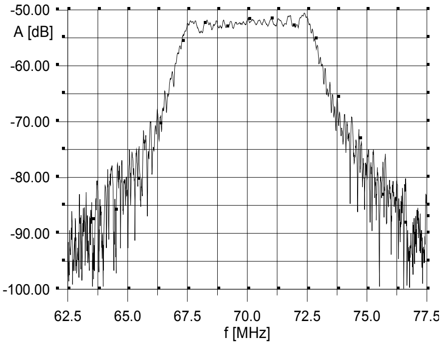

Fig. 9. Measured characteristic of expander.

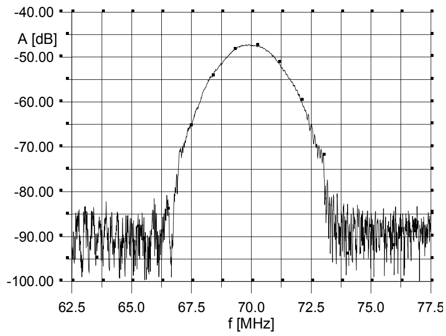

Fig. 10. Measured characteristic of compressor.

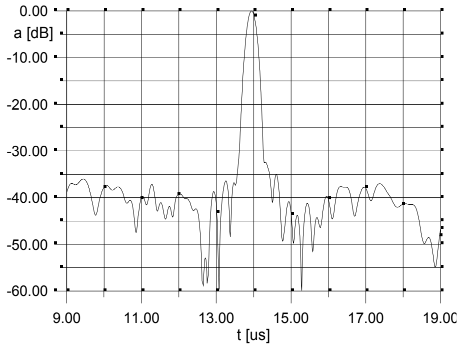

Fig. 11. Compressed signal.

5 Conclusion

The mathematical model developed for bandpass filters was implemented for dispersive delay lines design. The agreement between theory end experiment is very good.

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