SAW RESONATORS FOR TEMPERATURE STABLE OSCILLATORS

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Abstract – A double two-port resonator by means of which the compensation of the TCF1 as well as the TCF2 is possible is presented. The double resonator is composed of two coupled two-port single SAW resonators. The propagation directions are characterized by opposite and equal signs of TCF1 and TCF2, respectively. The coupling is realized by cascading and using a coupling inductance. In order to explain the TC compensation qualitatively a simple coupled spring resonator is treated analytically. An example of a double two-port resonator is studied by means of model calculations and experiments. 35.5° rotY quartz is used as a wafer material. The propagation angles (angle between the propagation direction and the X axis) of the single resonators are chosen to be larger and smaller, respectively, than the angle in vicinity of 45° whose TCF1 is zero. The frequency whose temperature stability is studied is defined as frequency belonging to a fixed phase. This phase is kept constant within the entire temperature range. The frequency and |S21| are calculated and measured as functions of temperature. Not only the theoretical but also the experimental results express the temperature shift of frequency from –30°C until 70°C to be essentially smaller than that in the case TCF1= 0 in vicinity of 45°.

I. INTRODUCTION

For many years, solutions of frequency determining surface acoustic wave (SAW) components for temperature stable oscillators have been searched. The most activities have been directed towards temperature stable cuts and propagation directions for SAW of quartz. Lam et al. [1] give an overview of work of the last 20 years. Dias et al. [2] report properties of the ST cut of quartz with the X axis as a propagation direction already in 1975 (Euler angles (0°,132.75°,0°)). As known, STX quartz has a parabolic temperature behavior because the temperature coefficient of frequency of 1st order (TCF1) vanishes. For ST-like cuts a second propagation direction with TCF1= 0 is found whose temperature coefficient of frequency of 2nd order (TCF2) is smaller than that for $\psi = 0$ (ψ is the angle to X axis). An example is presented in [3] (Euler angles (0°,123°,41.5°)). The so-called K cut (Euler angles (0°,96.5°,33.8°)) is a further example. The LST cut [5] (Euler angles (0°,~15°,0°)) is temperature stable for leaky SAW. Its temperature behavior in vicinity of room temperature is dominated by the TCF of 3rd order. Watanabe [6] describes a raised IDT structure to avoid the dependency of temperature behavior on electrode thickness.

Besides the search for temperature stable crystal cuts there is work to improve the temperature stability by design tools. A remarkable solution for delay lines (DL) on a ST cut of quartz was suggested by Browning and Lewis [7]. The design consists of the main DL with TCF1= 0 and the auxiliary DL with an almost linear temperature behavior. Both DL are connected in parallel. Magnitude and phase of the DL signals are chosen so that the signal, u_a, of the auxiliary DL is orthogonal to the resultant, u_r at the reference temperature T_0 as shown in Fig.1. As a result, the TCF2 is reduced. The purpose of the present paper is to suggest a resonator design that makes possible the compensation of TCF1 as well as TCF2.

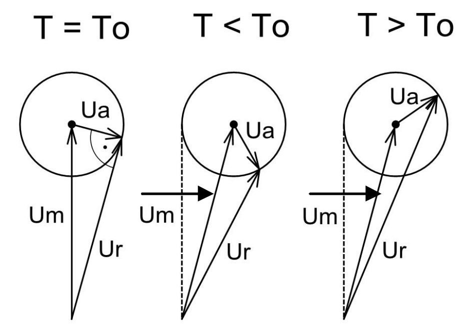


Fig.1. Pointer diagram of a delay line after Browning and Lewis [7].

II. TCF1 AND TCF2 COMPENSATION BY RESONATOR COUPLING

We consider two coupled spring resonators as a simple model of resonator coupling (Fig. 2). The

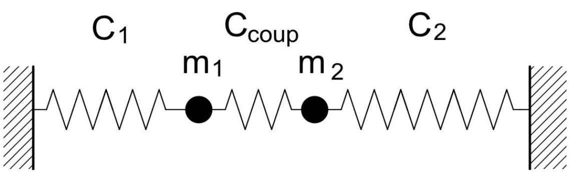


Fig.2. Coupled spring resonators.

single resonators are formed by the mass m_1 and the spring constant C_1 and by m_2 and C_2, respectively. They are coupled to each other by the spring C_{coup}. For the resonance frequencies we obtain

$$\omega_{1,2}^2=\left(\omega_{10}^2+\omega_{20}^2\right)/2\pm\sqrt{\left(\omega_{10}^2-\omega_{20}^2\right)^2/4+\gamma^2}$$
$$\omega_{10,20}^2=\left(C_{1,2}+C_{coup}\right)/m_{1,2},\ \gamma^2=C_{coup}^2/m_1 m_2 \qquad (1)$$

If $\left(\omega_{10}^2-\omega_{20}^2\right)^2/4<<\gamma^2$ is valid one approximately obtains

$$\omega_{1,2}^2\approx\left(\omega_{10}^2+\omega_{20}^2\right)/2\pm\left[|\gamma|+\left(\omega_{10}^2-\omega_{20}^2\right)^2/8\gamma\right] \qquad (2)$$

from Eq.(1). Now, we introduce temperature functions for ω_{10} and ω_{20} according to

$$\omega_{10,20}^2=\omega_0^2\left(1+a_{1,2}x+b_{1,2}x^2\right),\ x=T-T_0$$
$$\omega_0=\omega_{10}(T_0)=\omega_{20}(T_0) \qquad (3)$$

(T, T_0= temperature, reference temperature). From Eqs. (2) and (3) we obtain

$$\left(\omega_{1,2}/\omega_0\right)^2\approx A_0+A_1x+A_2x^2,\ A_0=1\pm|\gamma|/\omega_0^2,$$
$$A_1=\left(a_1+a_2\right)/2,\ A_2=\left(b_1+b_2\right)/2\pm\omega_0^2\left(a_1-a_2\right)^2/8|\gamma| \qquad (4)$$

From Eq. (4) we can conclude that the TCF1 and TCF2 are compensable if the conditions

$$a_1=-a_2\equiv a \text{ and } |\gamma|/\omega_0= a^2/\left(b_1+b_2\right) \qquad (5)$$

are met. From Eq. (5) it is found that the TCF2 of the upper and lower resonance is compensable if $b_1+b_2<0$ and $b_1+b_2>0$ is valid, respectively. By means of Eq. (5) the following requirements must be met by the single resonators.

- i The single resonators' TCF1 must have opposite signs.
- ii The coupling constant γ must be variable if a, b_1 and b_2 are given.

The consideration of the spring resonator is to be a guide for compensating the TCF1 and TCF2 of SAW resonators. As known, resonator coupling causes a resonance splitting. This effect is achieved by cascading two two-port SAW resonators as well. The above requirement ii to make the coupling constant variable can be met by introducing a coupling inductance. Opposite signs of TCF1 of single resonators according to Eq.(5) can be realized by using different propagation directions of ST quartz. Fig. 3 shows the schematic view of such a double resonator with cascading and coupling inductance. As an example we consider 35.5°rotY quartz and the propagation directions with the angles ψ= 42.5° and 47.5° with respect to X axis (Fig. 4).

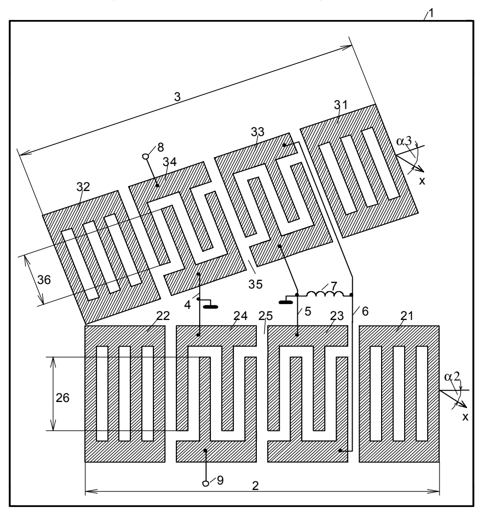


Fig.3. Schematic view of a SAW double resonator with cascading and coupling inductance.

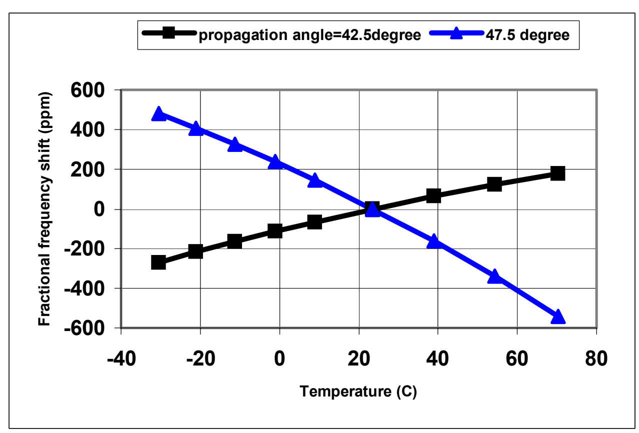


Fig.4. Experimental fractional frequency shift as a

function of ψ= 42.5° and 47.5° temperature for ψ= 42.5° and 47.5°, h_{Al}/λ= 3.75%

The TCF1 have opposite signs and TCF2< 0 is valid in both cases. That means b1,2< 0 in Eq. (3).

III. Analysis of Cascaded SAW Resonators

In this paper, we don't study real oscillators but we characterize SAW resonators under oscillator-like conditions by keeping the resonator phase constant in the entire temperature range. We determine the frequency belonging to this phase value as a function of temperature and call it oscillator frequency f_{osc}. The following steps are carried out.

i Calculation of temperature dependent synchronous frequencies of the single resonators based on experimental data,

ii choice of the phase φ_0 of S_{21} near to the considered resonance of the double resonator,

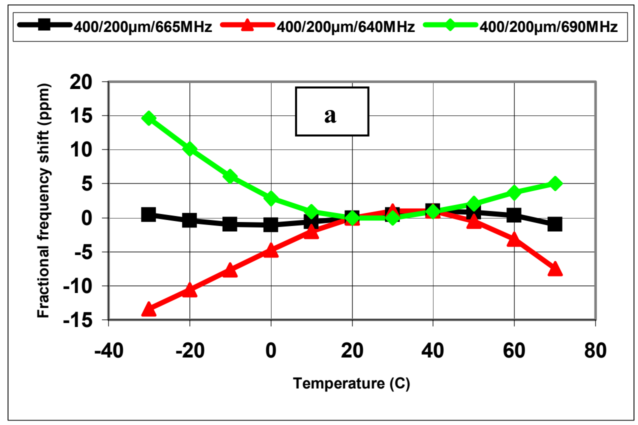
iii analysis of the double resonator at the current temperature and search for the frequency for which phase of S_{21}= φ_0 is met. Frequently φ_0 is set to zero.

Based on this conception the temperature shift of the oscillator frequency of a resonator example is calculated. The most important design parameters are summarized in Table 1.

Table 1. Design parameters of the resonator example.

PARAMETER	VALUE
wafer	35.5°Y quartz
propagation angle ψ (degree)	45.9/43.0
finger number of input/output IDT of double resonator	240
finger number of coupling IDT	360
frequency (MHz)	622
apertures (µm)	400/200
gap between IDTs (wavelengths)	0.30

Fig. 5a includes simulation results if the resonance frequency, f_c, of the coupling circuit (coupling IDT and coupling inductance) is varied. That corresponds to the variation of the coupling inductance, L_c, if the coupling IDT's capacitance is held constant. Fig. 5a shows that the value of f_c influences the curvature of the temperature behavior and consequently the TCF2. To vary f_c is equivalent to varying the coupling constant γ in Eq. (5). The complete compensation of TCF1 and TCF2 is theoretically achievable. As a result, the remaining temperature dependency is dominated by the TCF of 3rd order. As shown in Fig. 5b, the linear slope corresponding TCF1 can be corrected by varying the aperture ratio of single resonators. An similar effect is achieved by varying the finger number ratio of the coupling IDTs. The minimum variation of the oscillator frequency from –30°C until 70°C is approximately 1 ppm. It is expected that the experimental verification of this value will hardly be possible. But this result demonstrates the capability of the method.



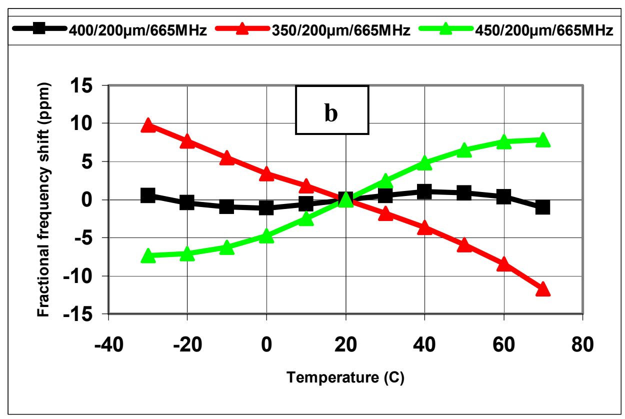
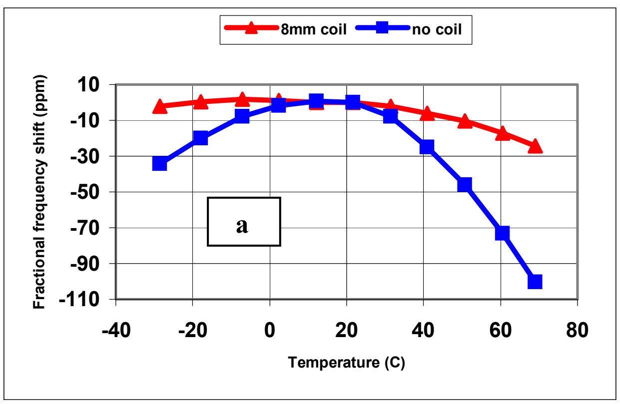


Fig.5. Simulation results of TCF compensation, a) TCF2 compensation by variation of f_c, b) TCF1 compensation by aperture ratio.

IV. Experimental Results

A double two-port resonator was implemented using the parameters of Table 1. The beam steering effect that is important for the chosen propagation directions is taken into account. As shown in Fig.3 the single resonators are cascaded. A coupling coil is employed. This coil is implemented as a simple wire loop of given length. The experimental temperature dependent shift of oscillator frequency is included in Figs. 6a and b. In Fig. 6a the influence of the coupling coil is studied. We find that the curvature (i.e. TCF2) is essentially decreased if a 8mm coupling coil is introduced. The maximum change of frequency shift from –30°C until 70°C drops from 101 to 26 ppm. The curve with the smaller curvature is also included in Fig. 6b. The second curve in Fig. 6b visualizes the slope reduction due to shortening the coupling IDT of 43° resonator by 20 finger pairs. This was done by disconnecting bus bars by a laser cutter. At the end of the tuning process we achieve 14 ppm for the maximum frequency shift. In this case, the experimental temperature dependency of $|S_{21}|$ at oscillator frequency is given in Fig. 7. The insertion loss varies by 3.5 dB (maximum value= 19 dB).



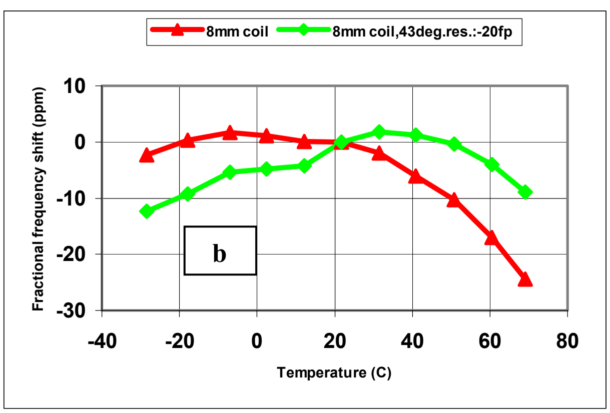


Fig.6. Experimental results of TCF reduction, a) TCF2 reduction by variation of L_c, b) TCF1 reduction by reducing finger pair number of 43° resonator by 20.

V. CONCLUSION

From the theoretical and experimental results we find the following rules of tuning the temperature behavior of the oscillator frequency.

i Curve is positively sloped → strengthen single resonator with TCF1< 0 by smaller aperture of single resonator with TCF1< 0 or larger aperture of single resonator with TCF1> 0. A negative slope can be reduced by inverse operations. Instead of aperture the finger number of coupling IDTs can be varied in an analogous way.

ii Curve is convex from below → increase resonance frequency of coupling circuit, f_c → decrease coupling inductance, L_c. A concave curvature can be reduced by inverse operations.

The achieved temperature stability is better than previously known.

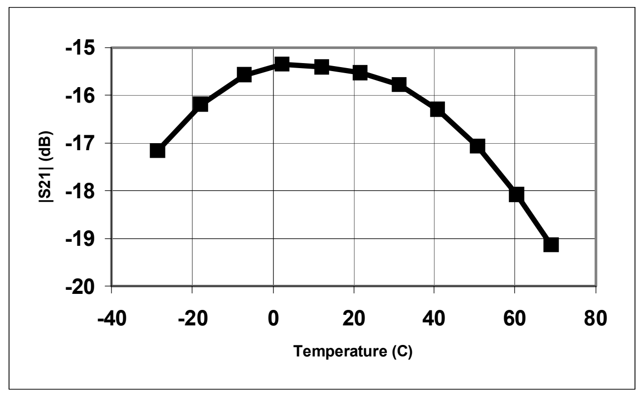


Fig.7. Experimental temperature dependency of $|S_{21}|$ at oscillator frequency.

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