Viscosity sensor with shear-horizontal acoustic plate mode on BT-cut quartz and surface acoustic wave filter for mode selection

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Shear horizontal acoustic plate mode (SHAPM) liquid viscosity sensor with the surface acoustic wave (SAW) filter for a chosen SHAPM selection was developed. A turnover temperature and a quadratic temperature coefficient of frequency of about 0°C and −25 ppb/(°C)², respectively, were obtained for a delay line on BT-cut quartz (−50.5°YX90°), with gold electrodes. An acoustically coupled resonator filter for a SHAPM selection was designed and fabricatedon the 38°YX cut quartz. With inductive coils of about 0.5 μH connected in series with a 50 Ω load, the measured IL of about 2 dB at a center frequency of about 100.4 MHz was obtained for the filter. For a SHAPM delay line with the filter, insertion loss, turnover temperature, and quadratic temperature coefficient of frequency of about 12 dB, 5°C, and −30 ppb/(°C)², respectively, were obtained. Insertion loss and frequency changes against product of mass density and viscosity were measured, using water and glycerin solutions. Insertion loss, and frequency changes of about 14 dB, and −18 kHz, respectively, were obtained, in a viscosity range from about 1 mPa·s to 1000 mPa·s.

Key words: quartz, acoustic plate modes, surface acoustic wave, delay line, resonator filter, viscosity sensor

Czujnik lepkości z poprzecznym akustycznym modem płytowym na kwarcu BT i filtrem z akustyczną falą powierzchniową do selekcji modu

Opracowano czujnik lepkości cieczy na poprzecznym horyzontalnym akustycznym modzie płytowym (PHAMP) z filtrem na akustycznej fali powierzchniowej (AFP) do selekcji wybranego modu. Dla linii opóźniającej na kwarcu o orientacji BT (−50,5°YX90°) ze złotymi elektrodami uzyskano paraboliczną zależność zmian częstotliwości w funkcji temperatury. Punkt zwrotny paraboli wystąpił dla temperatury około 0°C a współczynnik temperaturowy wyniósł około −25 ppb/(°C)². Filtr rezonatorowy z AFP zaprojektowano i wykonano na kwarcu o orientacji 38°YX. Z cewkami o indukcyjności około 0,5 μH, połączonymi seryjnie z obciążeniem 50 Ω, uzyskano tłumienność wtrącenia około 2 dB na częstotliwości 100,4 MHz. Dla linii opóźniającej połączonej kaskadowo z filtrem, uzyskano tłumienność wtrącenia około 12 dB, punkt zwrotny paraboli wystąpił w temperaturze 5°C, a współczynnik temperaturowy wyniósł około −30 ppb/(°C)². Do pomiaru zmian tłumienności wtrącenia i częstotliwości w funkcji iloczynu gęstości masy i lepkości dynamicznej zastosowano wodne roztwory gliceryny. W zakresie lepkości od 1 mPa·s do 1000 mPa·s, uzyskano zmianę tłumienności wtrącenia o 14 dB i częstotliwości o −18 kHz.

Słowa kluczowe: kwarc, akustyczne mody płytowe, akustyczna fala powierzchniowa, linia opóźniająca, filtr rezonatorowy, czujnik lepkości

1. Introduction

Shear horizontal acoustic plate modes (SHAPMs) in BT-cut quartz are attractive for the application in viscosity sensors [1]. However, for the application in an oscillating system, a low loss and narrow bandwidth filter should be used to sufficiently attenuate both the surface transverse wave (STW) and the other SHAPMs. Because SHAPMs in BT-cut quartz are temperature compensated, the filter should also possess a similar property. The surface acoustic wave (SAW) in-line acoustically coupled resonator filter [2] with aluminum electrodes [3] on Y rotated cut of quartz [4] was therefore chosen for this application. This paper presents calculations and measurements of such filter and properties of a viscosity sensor.

2. SHAPM delay line with gold electrodes

It was previously shown that an insertion loss of about 10 dB at a frequency of about 100.4 MHz was obtained [1] for a sufficiently thick aluminum layer (0.6 μm), and after compensation of static capacitances of long interdigital transducers (IDTs) of a delay line by means of inductors (60 nH). As gold electrodes are more reliable for the operation of a viscosity sensor, in this work, the structure of the delay line with a gold layer thickness of about 0.2 μm was deposited on the delay line plane of a quartz plate, whereas the opposite sensing plane was covered with a 0.1 μm thick continues gold layer (Fig. 1).

Measured spectrum of SHAPMs and amplitude response of the chosen mode are presented in Fig. 2

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and 3, respectively. Compared to aluminum electrodes [1], a turnover temperature and a quadratic temperature coefficient of frequency of the chosen SHAPM are now about 0°C and −25 ppb/(°C)^2, respectively.

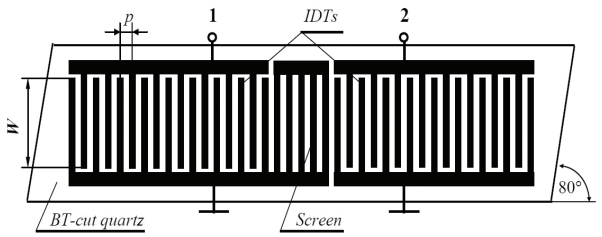


Fig. 1. Structure of the delay line.
Rys. 1. Struktura linii opóźniającej.

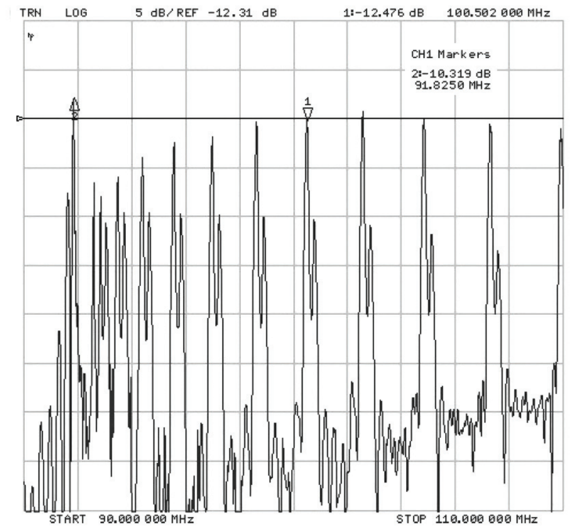


Fig. 2. Amplitude spectrum in the air.
Rys.2. Widmo amplitudowe w powietrzu.

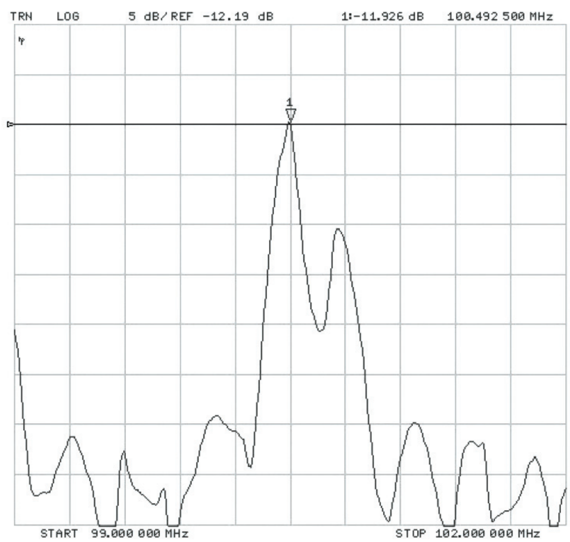


Fig. 3. Amplitude response of the chosen mode.
Rys. 3. Charakterystyka amplitudowa wybranego modu.

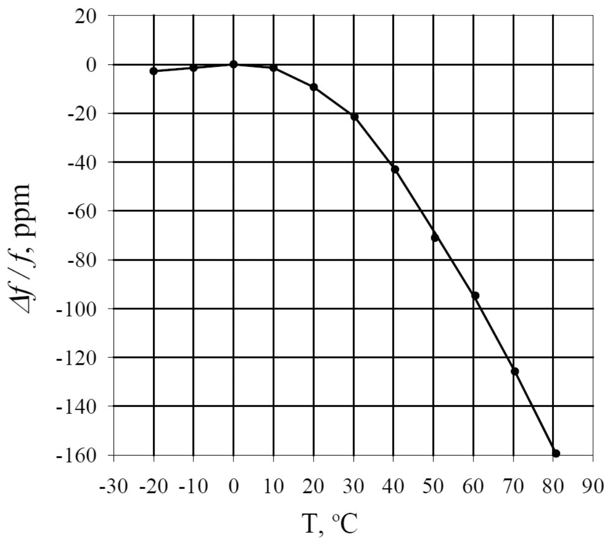


Fig. 4. Relative changes of frequency against temperature for gold electrodes.
Rys. 4. Względne zmiany częstotliwości w funkcji temperatury dla złotych elektrod.

3. Calculations and measurements of SAW filter

The SAW symmetrical in-line acoustically coupled resonator filter consists of two IDTs, one center and two end reflectors (Fig. 5) [2]. The IDTs are apodized to eliminate SAW transverse modes. Here W is the aperture, p_1 and p_2 are the electrode periods of the reflectors and the IDTs, respectively, and l is the distance between the center of the IDT electrode and the edge of the reflector electrode. The edges of quartz substrate were cut at an angle of 80° to scatter SAW propagating outside the reflectors.

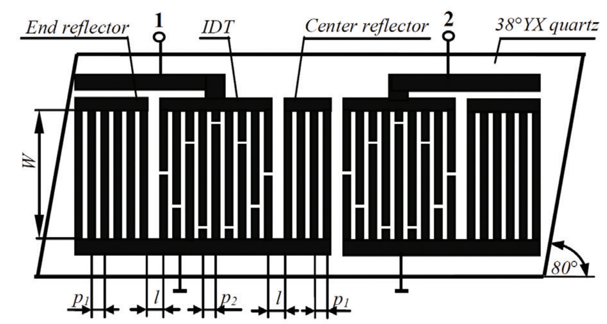


Fig. 5. Structure of symmetrical acoustically coupled resonator filter.
Rys. 5. Struktura symetrycznego filtru rezonatorowego ze sprzężeniem akustycznym.

The transfer function A_{12} of the filter can be written as [2]:

$$A_{12} = \frac{G_{12} P_0^2}{(P_1 - G_{11} P_2)^2 - (G_{12} P_2)^2}, \tag{1}$$

$$P_0 = tS_{13}[1 + r\,(S_{12} - S_{11})], \tag{2}$$

$$P_1 = 1 - rS_{11}, \tag{3}$$

$$P_2 = t^2\,[r\,(S_{12}^2 - S_{11}^2) + S_{11}], \tag{4}$$

$$t = T_i\,\exp(-j\Theta), \tag{5}$$

$$r = \Gamma\,\exp\,(-j2\Theta), \tag{6}$$

$$\Theta = \omega\left(\frac{1}{v_f} + \frac{(N_t - 1)\,p_2/2}{v_t}\right). \tag{7}$$

$S_{i,j}$ (i, j = 1, 2, 3) are the scattering coefficients of the IDT [2]; G_{kl} (k, l = 1, 2) are the scattering coefficients of the center reflector; T_i is the loss coefficient; Γ is the reflection coefficient of the end reflector; v_f is the free surface SAW velocity; v_t is the SAW velocity in the areas of the IDTs and the reflectors and N_t is the number of the IDT electrodes.

Admittance of an apodized IDT with internal reflections, required for determination of S_{ij}, can be determined by the multichannel method [5]. In this method, the IDT is divided into sufficient number of channels which are connected in parallel. Admittance of each channel is calculated from an analytical expression presented in [6 − 7].

Insertion losses *IL* of the filter can be calculated from the expression

$$IL = -20\,\log\,|A_{12}| \tag{8}$$

This filter should possess low insertion loss at a frequency of the chosen mode, it should suppress the other modes, and it should be fabricated on a temperature compensated substrate.

Taking into account the effect of the turnover temperature changes caused by the aluminum layer [3], the 38°YX cut quartz was chosen for the filter [4]. The following data of SAW on this cut were used for the design of the filter: v_f = 3154 m/s, v_t = 3136 m/s, K_2 = 0.125% [4], $\gamma = -0.62\,h/\lambda$, where v_f, K_2, γ, h and λ and are the free surface velocity, square of the electromechanical coupling coefficient, reflection coefficient of a single strip of the IDT, thickness of the aluminum layer and SAW wavelength, respectively. It was found that, aluminum layer thickness of about 0.6 μm should be used to obtain sufficient bandwidth of the filter. The following data were obtained for the final structure of the designed filter: W = 2.5 mm, p_1 = 15.57 μm, p_2 = 15.45 μm, N_t = 101, N_e = 250 and N_c = 10, where N_t, N_e and N_c are the number of electrodes of the IDT, the end and the center reflectors, respectively. The loss coefficient T_i = 1 (no losses) was used for the design.

The filter was fabricated by the lift-off method, mounted in metal packages and measured (using Agilent Network Analyzer Type 8753ET, Santa Rosa, CA). The measured and calculated amplitude responses with inductive coils of about 0.5 μH connected in series with the 50 Ω load, are shown in Fig. 6. The measured *IL* of about 2 dB at a center frequency of about 100.4 MHz was obtained. To obtain the same reference level as the one received in the measurement necessitated, the use of the loss coefficient T_i = 0.954 in the calculation.

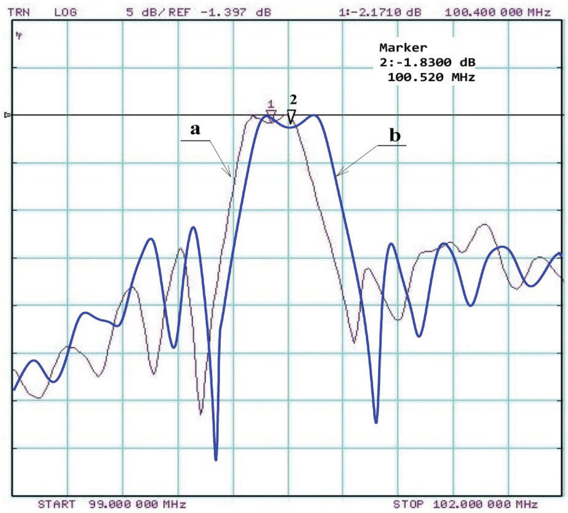


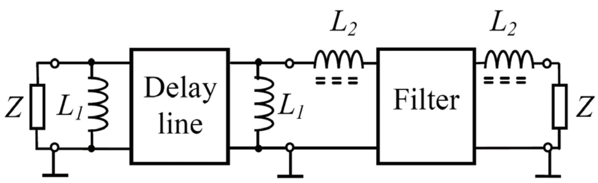
Fig. 6. Measured (a) and calculated (b) amplitude responses of the filter.

Rys. 6. Zmierzona (a) i obliczona (b) charakterystyki amplitudowe filtru.

4. Properties of viscosity sensor

The SHAPM delay line and SAW filter with matching inductors were connected in cascade (Fig. 7) and measured in the air (Fig. 8 − 9). All other modes were attenuated by more than 20 dB with respect to the chosen mode. For the SHAPM delay line with the filter we obtained, insertion loss, turnover temperature, and quadratic temperature coefficient of frequency of about 12 dB, 5°C, and −30 ppb/(°C)^2 in the air, respectively.

Insertion loss ΔL and frequency changes Δf against $\sqrt{\rho\eta}$, where ρ [g/cm^3] and η [mPa·s] are the mass density and viscosity of glycerin and water solutions, respectively and are shown in Fig. 10. In a viscosity range from about 1 mPa·s to 1000 mPa·s, the obtained insertion loss and frequency changes were about 14 dB, and −18 kHz, respectively.



Z = 50 Ω, L_1 = 60 nH, L_2 = 0.5 μH

Fig. 7. Delay line and filter with matching inductors.

Rys. 7. Linia opóźniająca i filtr z cewkami dopasowującymi.

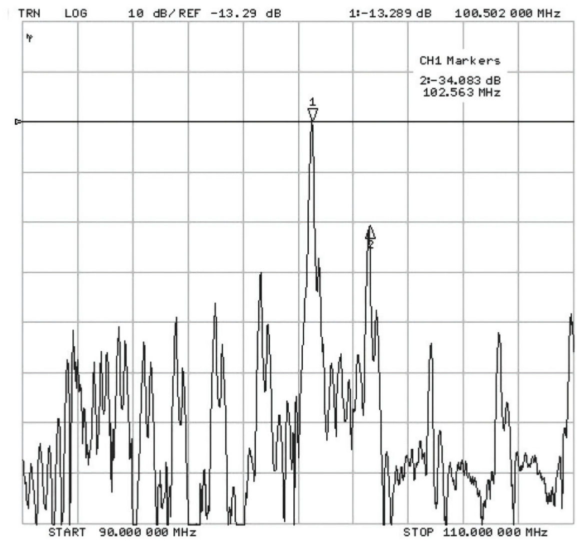


Fig. 8. Amplitude response of sensor with filter.
Rys. 8. Charakterystyka amplitudowa czujnika z filtrem.

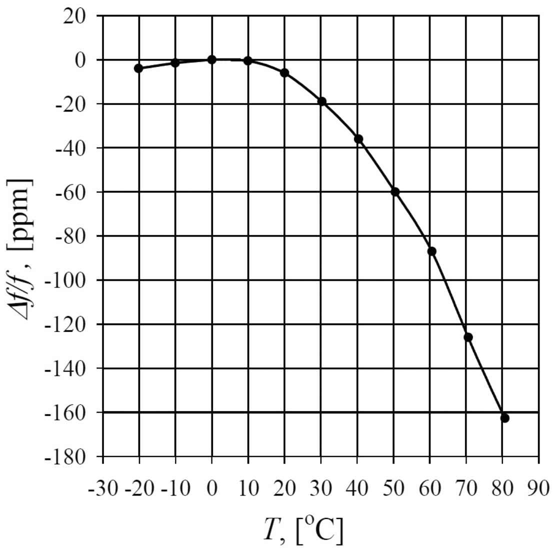


Fig. 9. Relative frequency changes against temperature.
Rys. 9. Względne zmiany częstotliwości w funkcji temperatury.

5. Conclusions

SHAPM viscosity sensor with SAW filter was developed. A turnover temperature and a quadratic temperature coefficient of frequency of about 0°C and −25 ppb/(°C)^2, respectively, were obtained for a delay line on BT-cut quartz (−50.5°YX90°) with gold electrodes. The SAW in-line acoustically coupled resonator filter for the SHAPM selection in BT-cut quartz was designed and fabricated on the 38°YX cut quartz. For the SHAPM delay line with the filter, insertion loss, turnover temperature, and quadratic temperature coefficient of frequency of about 12 dB, 5°C, and −30 ppb/(°C)^2 in air, respectively, were obtained. Using water and glycerin solutions, insertion loss and frequency changes against product of mass density and viscosity.

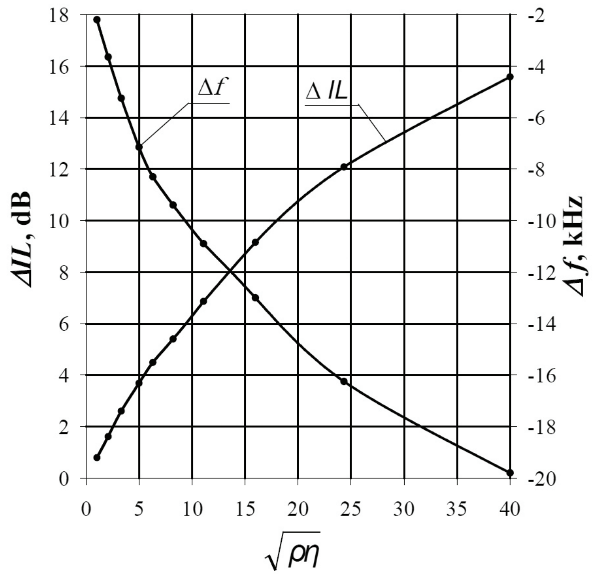


Fig. 10. Insertion loss (ΔIL) and frequency (Δf) changes against $\sqrt{\rho\eta}$.
Rys. 10. Zmiany tłumienności wtrącenia (ΔIL) i częstotliwości (Δf) w funkcji $\sqrt{\rho\eta}$.

In a viscosity range from about 1 mPa·s to 1000 mPa·s, insertion loss and frequency changes of about 14 dB, and −18 kHz, respectively, were obtained.

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