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A new approach to test set for SAW delay line based gas sensors

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***Abstract*—The paper presents a new switchable test set dedicated to dual delay line surface acoustic wave (SAW) gas sensors. It operates at frequency of 205 MHz utilizing dual delay line fabricated by SAW Components. The sensor detects traces of dimethyl methylphosphonate (DMMP) that is a simulant of combat poisoning agents. The test set described is built of a single oscillator adopting commutation of two SAW delay lines and this way has better thermal properties than commonly used networks consisting of two independent oscillators. Its measured frequency to temperature is ten times lower than obserwed for double oscillator networks. Additonaly due to alteranate operation of the sensors the interaction between delay lines built on common substrate is eliminated. This work was presented at the 53th Winter School on Wave and Quantum Acoustics [1] February, 24 – 27, 2025, DOI 10.5162/20WWonAE/A7.**

***Keywords*—switchable oscillator; delay line; surface acoustic wave (SAW); dimethyl methylphosphonate (DMMP); poisoning agents; digital transducer**

I. Introduction

THE application of surface acoustic wave (SAW) in electronics and sensor technology began more than five decades ago. Today, thanks to the use of miniaturized finger transducers (IDTs) utilized in quartz delay lines, it is possible to generate high-frequency SAW in piezoelectric materials [2].

They have found application in many fields of science and industry, serving in the detection of single solid particles contained in the air [3], or even in the textile industry [4] as sensors to determine the tension of the yarn. They are also widely used in the measurement of micro-pressures [5],[6] and even the concentrations of oils distributed in fuel mixtures [7].

SAW gas sensors are delay lines with additional thin layers of adsorber placed their surfaces. Such structures are often characterized by very high sensitivity, which is a consequence of the high concentration of surface wave energy in the superficial region of the SAW substrate. Therefore, even small changes in adsorbing material parameters have a measurable influence on wave propagation [8]. The designers of modern SAW sensors are mainly focused on obtaining high sensitivity and fast response rates, which is preferred for the determination of trace amounts of toxic gaseous substances [9]. Sensor structures adopting SAW operation principles can easily convert chemical reactions between the adsorbing material used and the traced gas molecules (vapour) into measurable electrical signals, e.g. frequency changes of oscillators. For the manufacturing of such sensors, a wide range of materials having a special chemical design is used to form thin adsorbing layers in the two-layer and even multi-layer structures. The appropriate selection of a specific receptor material for a specialized sensor structure mainly depends on the ease of synthesis, good adherence to the piezoelectric substrate [10], obtained sensitivity and selectivity [11], and time of regeneration [12],[13]. The detection of gaseous substances also depends on the electromechanical coupling of the adsorbing layer with the substrate, the ambient temperature and the design of the measuring chamber. Commonly used SAW devices are transducers that are delay lines or passband filters. The reaction of the SAW sensor to changes in the concentration of gas particles in its environment is manifested by a change in the wave velocity within the substrate, its phase or amplitude which results in changes in the electrical parameters of a transducer.

Variation of SAW sensors parameters could be measured by means of commercial vector network analysers or phase-gain meters. However, it is possible to perform this operation with the simpler dedicated electronics circuits. Popular and widely applied method is adoption of sinusoidal oscillators utilizing SAW sensors as elements stabilizing frequency of oscillations – this way oscillation frequency could be dependent on parameters of SAW sensor.

Therefore, the change in acoustic wave velocity that is the reaction for the gas or vapour molecules in the sensor surrounding atmosphere is turned into oscillation frequency shift. [14]-[17]. The main issue of adoption of oscillating test sets is attenuation introduced by the sensor to the feedback loop of the oscillator and its electrical matching. [18].

But from the other hand this kind networks could provide high resolution of measurements.

In this paper the structure and properties of an oscillator adopting switching of sensors that operates at frequency of about 205 MHz and have decreased sensitivity to ambient temperature is described.

Described measurement test set utilizing the dual delay SAW line fabricated by SAW Components was adopted for detection of trace amounts of a DMMP simulant of combat poisoning agents (Dimethyl methylphosphonate) in the air [19]-[23].

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II. THEORETICAL BACKGROUND

Oscillators cooperating with SAW delay lines have the structure shown in the Fig. 1, and are constructed of looped amplifier and delay line to form a positive feedback network. In this network, the delay line is the element that determines the oscillation frequency.

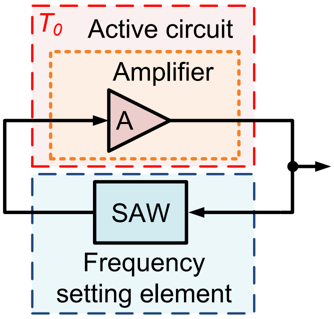
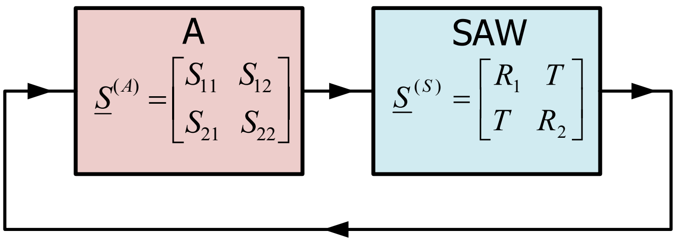


Fig. 1. Block diagram of example oscillator with frequency stabilized by SAW delay line.

The properties of such an oscillator can be described using the scattering matrices of the amplifier and SAW delay line. The mathematical description of the network shown in Fig. 1 is given in the block diagram in Fig. 2, where $\underline{S}^{(A)}$ is the scattering matrix of the amplifier and $\underline{S}^{(S)}$ is the scattering matrix of the SAW delay line.



$$\underline{S}^{(A)} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \qquad \underline{S}^{(S)} = \begin{bmatrix} R_1 & T \\ T & R_2 \end{bmatrix}$$

Fig. 2. Scattering model of example oscillator. Where A is active part of the oscillator network and SAW is an acoustic delay line.

As the SAW delay line is a symmetrical passive two-port network its forward and backward transmission coefficients are even end marked T. The input and output reflection coefficients of the SAW delay line are marked as R_1, and R_2 respectively. The frequency behaviour of the modulus $|T|$ and phase φ of transmission coefficient T are depicted in Fig. 3.

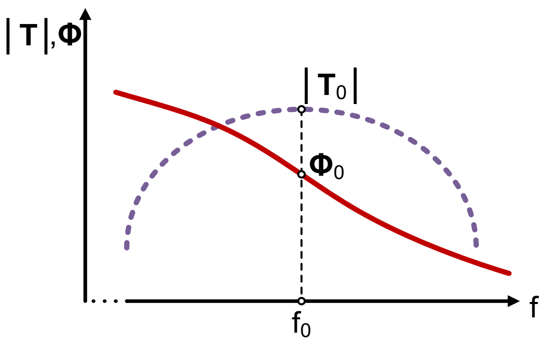


Fig. 3. Example amplitude-phase characteristic of transmission coefficient $\underline{S}^{(s)}$ [24].

Characteristic of $|T|$ has a maximum at frequency f_0. The oscillations will occur within the network described in the diagram from Fig. 2 when condition (1) is met at the frequency f_0 [24].

$$det\left[\underline{S}^{(A)} \cdot \underline{S}^{(S)} - \underline{1}\right] = 0 \tag{1}$$

The condition (1) could be rewritten after transformations as (2) [24].

$$(S_{21A} + S_{12A})T + S_{11A}R_1 + S_{22A}R_2 - \Delta^t\Delta^s = 1 \tag{2}$$

where Δ^t and Δ^S are determinants of the scattering matrices $\underline{S}^{(A)}$ and $\underline{S}^{(S)}$. As it was shown, the excitation of oscillations in the described network depends on all scattering parameters of the amplifier and SAW delay line. Both scattering parameters of the amplifier and SAW depend on temperature. Therefore, fulfillment of condition (2) is temperature-dependent in a complex way. The effect could be reduced by adopting a matched amplifier which $S_{11} = S_{22} = 0$. This simplifies condition (2) giving (3).

$$S_{21A} \cdot T = 1 \tag{3}$$

The fulfilment of the condition (3) by the oscillator network at the frequency f_0 requires the value $Im(S_{21A}T) = 0$ to be obtained. The above, in the case of existing phase shifts introduced by the amplifier and the delay line necessitates the application within the oscillator loop of an additional phase shifter as shown in Fig. 4.

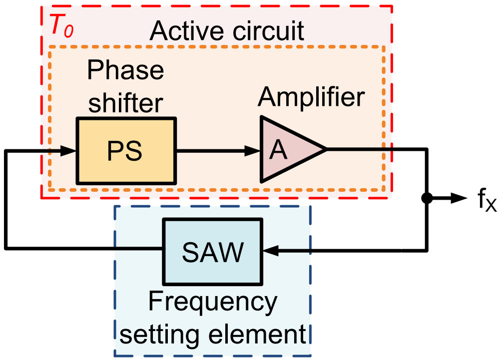


Fig. 4. Block diagram of SAW oscillator containing additional phase shifter PS.

If the ports of the amplifier and the phase shifter are matched, and the amplifier is unilateral the scattering matrices of the amplifier $\underline{S}^{(A)}$ and phase shifter S_{PS} are:

$$\underline{S}^{(A)} = \begin{bmatrix} 0 & 0 \\ S_{21A} & 0 \end{bmatrix} \tag{4}$$

$$S_{PS} = \begin{bmatrix} 0 & T_{PS} \\ T_{PS} & 0 \end{bmatrix} \tag{5}$$

The block diagram of the network extended with the phase shifter is given in Fig. 5.

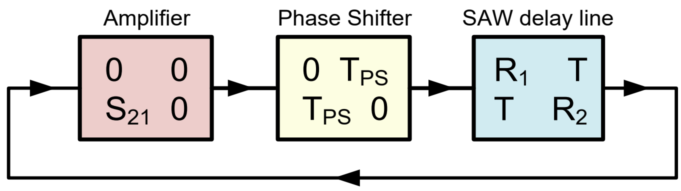


Fig. 5. Scattering model of SAW oscillator containing additional phase shifter.

The condition (3) for the network given in Fig. 4 could be written as two separate equations describing: the amplitude (6), and the phase (7) conditions of oscillations.

$$|S_{21A}| \cdot |T_{PS}| \cdot |T_{SAW}| = 1 \tag{6}$$

$$\varphi_{Amp} + \varphi_{PS} + \varphi_{SAW} = 2\pi n \tag{7}$$

where: $|T_{PS}|$ - is the modulus of the transmission coefficient of the phase shifter, φ_S is its phase shift. The relationship between the phase shift of the SAW delay line and frequency can be near its oscillation frequency approximated by a linearized equation (8).

$$\varphi_{SAW} = \varphi_0 + kf \tag{8}$$

where: k describes the slope of the phase characteristic versus frequency and φ_0 is its phase offset. Using the expressions (7) and (8), the value of the oscillation frequency f for the network can be written as:

$$f = \frac{2\pi - \Psi - \varphi_0}{k} \tag{9}$$

where:

$$\Psi = (\varphi_{Amp} + \varphi_{PS}) \tag{10}$$

III. Description of the New Measuring Method

The oscillation frequency of the SAW delay line is under the influence of the detected agent and the ambient temperature. The sensitivities for the agent and the temperature are similar. The frequency sensitivity to temperature is caused by the mechanical parameters of the sensor and sensor well as electronic circuit. For the sake of temperature influence on the SAW properties, there are often adopted test sets in which two oscillators are used simultaneously. The first oscillator incorporates the active SAW sensor reacting to the changes in gas concentration and the second one incorporates the reference sensor (Fig. 6a). The response of the test set to the detected agent is frequency shift of first oscillator, the output is frequency difference between the two oscillators.

This method is correct when temperatures of both adopted delay lines are the same and both oscillators have the same sensitivity to temperature. Therefore, the two delay lines are often made on a common substrate, which guarantees the same temperature for active and reference sensors. However, it is difficult to assume that both active networks within the oscillators are identical and that thermal changes of their parameters that occur under operating conditions are identical might not be true.

In an active network, the temperature influence on scattering parameters (both their modules and phase shifts) is observed. These phenomena stem from the temperature changes of their operating points and transit frequencies. The issues concerning the temperature influence on amplifier parameters are widely described [25]-[29]. The dual oscillator SAW test sets have active systems built of two separate sets of elements that differ in electrical parameters and thermal response. In order to reduce the temperature influence on the active networks the authors have proposed a single active network that is switched between reference and sensor lines of the SAW as shown in Fig. 6b. Thanks to this solution, both SAW sensors share the same active network. In addition, the crosstalk present between the two delay lines fabricated on a common substrate is troublesome for the test sets with two simultaneously operating oscillators. In the proposed solution SAW delay lines operate exclusively, which eliminates the problem of mutual crosstalk. Therefore, in contrast to commonly used systems where signals from both sensors are obtained simultaneously, in the proposed solution the signals are generated alternately.

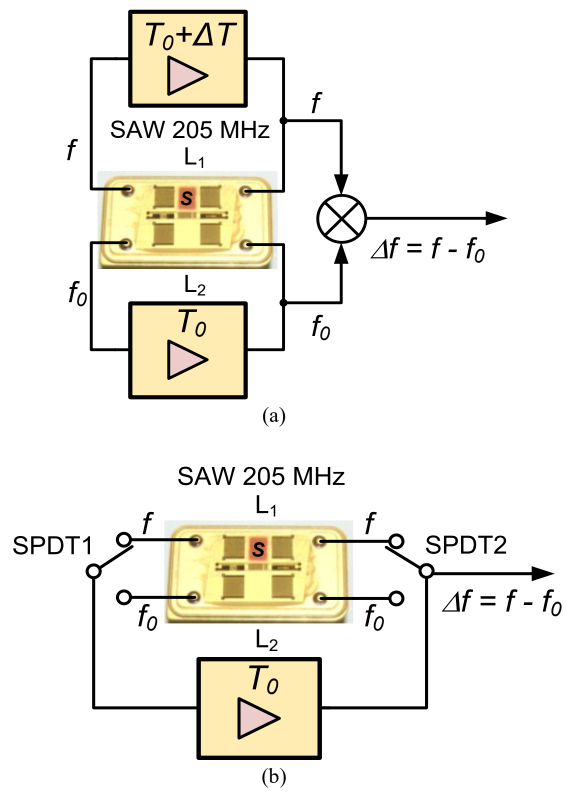


Fig. 6. (a) A commonly used measurement method adopting two simultaneously operating oscillators to excite the reference and measurement sensors, (b) described test set built of an active network shared among SAW delay-lines.

The effect of the temperature gradient between the two active networks on the output frequency difference of two SAW delay line generators can be demonstrated using the following simplified temperature analysis. For small temperature changes the phase shift Ψ (10) is linearly dependent on the temperature:

$$\Psi = \Psi(T_0) + \psi\Delta T \tag{11}$$

where Ψ - is the phase shift of the active network at temperature T_0 and ψ - is the temperature phase shift coefficient. Assuming that the temperature of active networks of the first and second oscillators are T_0 and $T_0+\Delta t$ respectively, the phase shift Ψ' of the first active network and Ψ'' are:

$$\Psi' = \Psi'(T_0) \tag{12}$$

$$\Psi'' = \Psi''(T_0) + \psi''\Delta T \tag{13}$$

According to (9) and (11) the oscillation frequency f_1 of the first oscillator is:

$$f_1(T_0) = \frac{2\pi n - \Psi\prime(T_0) - \varphi_0}{k_1} \tag{14}$$

Frequency f_2 of the second oscillator is:

$$f_2(T_{T_0+\Delta T}) = \frac{2\pi n - \Psi\prime\prime(T_0) + \psi\prime\prime\Delta T - \varphi_0}{k_2} \tag{15}$$

The frequency difference between the two simultaneously operating oscillators is:

$$\Delta f = f_2 - f_1 = 2\pi n \cdot \frac{k_1 - k_2}{k_1 k_2} + \frac{\Psi\prime k_2 - \Psi\prime\prime k_1}{k_1 k_2} + \frac{\varphi_0 k_2 - \varphi_0 k_1}{k_1 k_2} \tag{16}$$

For the test set having simultaneously operating oscillators the frequency component $\Delta fs(\Delta T)$ depending on temperature gradient ΔT is:

$$\Delta fs(\Delta T) = -\frac{\psi\prime\prime\Delta T}{k_2} \tag{17}$$

Based on the previous considerations, a switchable measurement test set can be analyzed. In such a network, the temperature of the active part is the same for both sensors. Therefore, the phase shift of the active network versus the temperature is:

$$\Psi' = \Psi'' = \Psi(T_0) + \psi\Delta T \tag{18}$$

So, the frequency component $\Delta fc(\Delta T)$ for the switched test set is:

$$\Delta fc(\Delta T) = \psi\Delta T \frac{k_2 - k_1}{k_2 k_1} \tag{19}$$

Comparing (17) and (19) it is visible that the influence of the temperature of the oscillator active network on the frequency is in the switchable test set significantly smaller than in the one build of two independent oscillators. The idea of a switchable test set has been implemented practically in a circuit which block diagram is shown in Fig. 7.

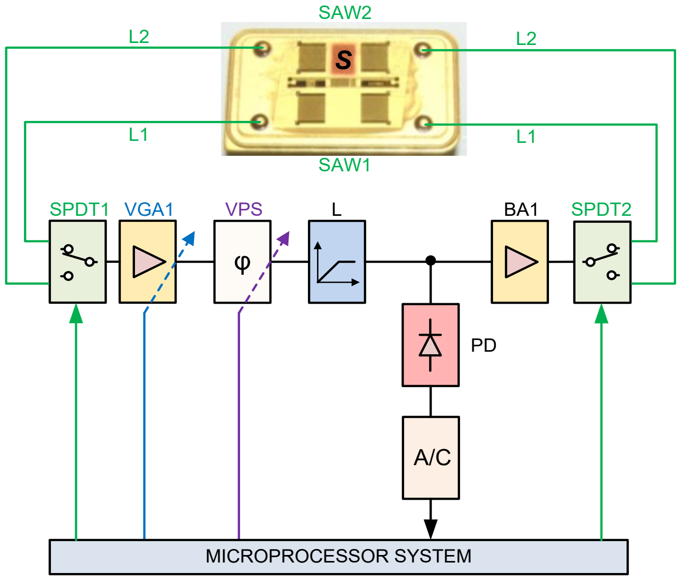


Fig. 7. E diagram of dedicated 205 MHz switchable SAW oscillator network.

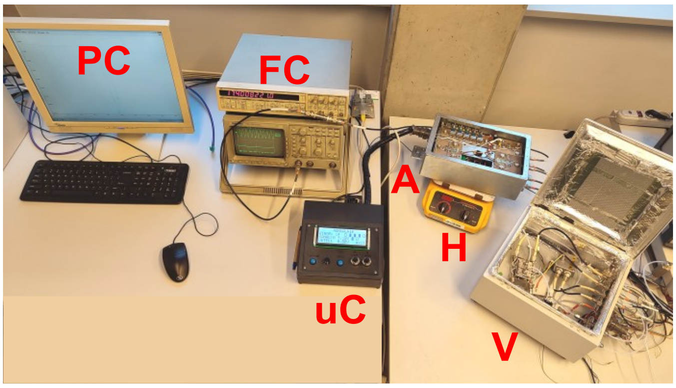
The system consists of two SPDT switches, VGA1 - variable gain amplifier, VPS - multi-state phase shifter, L- amplitude limiter, PD - peak detector, A/D converter, VGA1 and BA1 - two broadband amplifiers, and a microprocessor system. Switches SPDT1 and SPDT2 are adopting PIN diodes in such a way that changing their temperature does not affect the electrical symmetry of the circuit. All parts are controlled by a microprocessor system. The VGA1 amplifier is a microprocessor-adjustable gain block and is used together with the peak detector circuit to determine the gain value that meets the generation conditions for the optimal amplitude of the output signal avoiding the occurrence of a high level of harmonics. The excessive gain will cause a large amplitude of oscillations and non-linear distortions within the output signal. The non-linear distortions of the signal introduce the harmonics of the signal which affects the frequency change according to the nonlinear frequency correction [24]-[29] which shows the frequency dependency on the amplitude of harmonics.

The important element affecting the frequency of oscillations of the network is the phase shifter. It is shown in (9) that a change in the phase shift introduced by the shifter has the same effect on frequency as a change in the phase shift introduced by the sensor. The high sensitivity of the frequency generated by the system for the phase shift requires the adoption of a shifter characterized by high phase stability. So, in the described test set, a multi-state phase shifter consisting of 32 sections of the coaxial transmission line is applied. The described oscillator employs a broadband active amplitude limiter L which separates amplitude limiting from amplification functions. Thanks to this solution, the correlation of the signal amplitude and frequency is small. The active network applied in the test set is broadband with well-matched input and output ports eliminates matching networks, which minimizes the influence of the temperature on its phase shift.

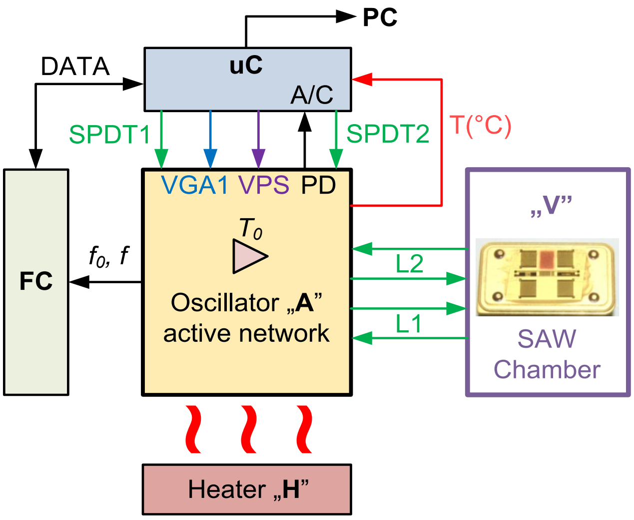
IV. Experimental Results

The described oscillator is dedicated to DMMP detection.

It was assembled according to the photo and schematic diagram given in Fig. 8.



(a)



(b)

Fig. 8. The measurement test set used measurements of the sensitivity to temperature of the oscillator active network: a) is a real photo, b) schematic diagram.

The test set is built of the earlier described switched oscillator consisting of two sensors SAW1 and SAW2, connected to the single active network by switches SPDT1, and SPDT2. Both sensors are placed in chamber V. The control functions such as switching SPDT1, SPDT2, switching phase shifter VPS, reading signal amplitude A/D and reading frequency FC meter output are controlled by the microprocessor uP. The temperature of the active network is changed by the heater. The effect of the device heating is shown in Figs. 9-11.

The frequency shift observed for two separated individual oscillators is 4kHz for the ambient temperature increment of 25 °C that gives 0.78 ppm/°C. The difference in frequency of a couple of oscillators for the same temperature increment is 390 Hz that correspond to 0.076 ppm/°C [1].

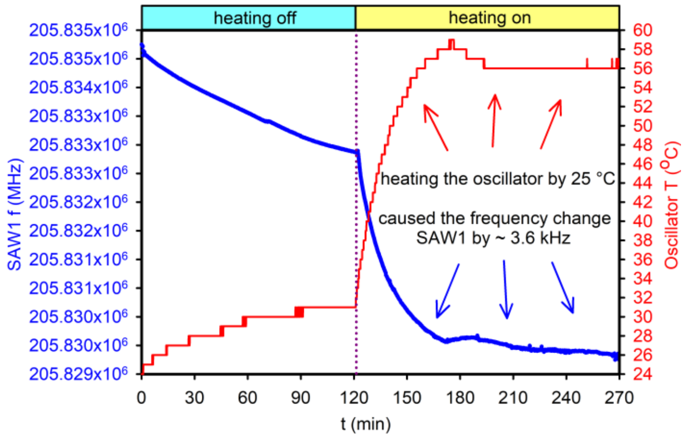


Fig. 9. Frequency–time response of heated oscillator including SAW1 sensor.

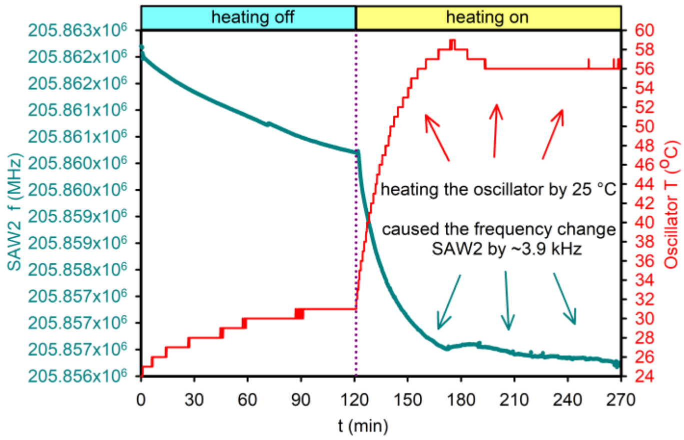


Fig. 10. Frequency–time response of heated oscillator including SAW2 sensor.

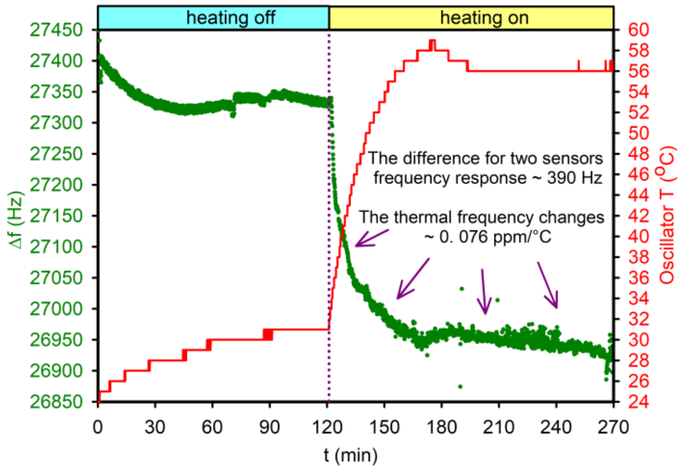


Fig. 11. Difference of the responses of test set observed for SAW1 and SAW2 connected successively.

It is visible that the proposed oscillator adopting an active network common for the two sensors has a temperature-influenced frequency change that is about 10 times smaller than in the case of each single oscillator. In order to verify of the results, the frequency change ratio (*FCR*) was found adopting the formulas (17) and (19).

$$FCR = \frac{\Delta fs(\Delta T)}{\Delta fc(\Delta T)} \quad (20)$$

For first oscillator including SAW1 sensor and for second including SAW2 sensor *FCR1* and *FCR2* are accordingly (21), (22).

$$FCR1 = \frac{-\frac{1}{k_2}}{\frac{k_2-k_1}{k_2 \cdot k_1}} \quad (21)$$

$$FCR2 = \frac{-\frac{1}{k_1}}{\frac{k_2-k_1}{k_2 \cdot k_1}} \quad (22)$$

The phase slopes k_1 and k_2 were read from the characteristics of the S_{21} phase of the SAW sensors measured around the oscillation frequencies, within the range of 1 kHz and given in Fig. 12 and Fig. 13. In the vicinity of the oscillation frequencies, the values k_1 and k_2 are:

$$k_1 = \frac{2{,}449}{2} \cong 1{,}2° \quad (23)$$

$$k_2 = \frac{2{,}886}{2} \cong 1{,}4° \quad (24)$$

which gives *FCR1* ~ 5,9 and *FCR2* ~ 6,4:

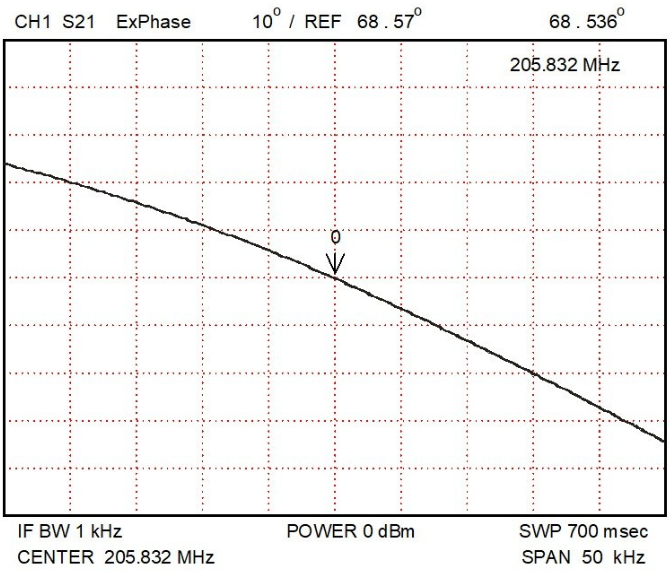


Fig. 12. Characteristics of the S_{21} phase of the SAW sensors in the vicinity of the oscillation frequency for sensor SAW1.

The FCR value computed using presented simplified model is 6.4 which means that theoretical frequency shift for the test set adopting switched SAW sensors and common active part of the oscillator is 6.4 smaller than frequency shift of a single oscillator including SAW sensor. The measured FCR is about 10. The difference between the theoretical and measured *FCR* is less than 36%.This is caused by the nonlinear phase response of SAW sensors depicted in Fig. 12-13 and stem from the assumption of linear phase response of SAW delay line within the adopted within theoretical model.

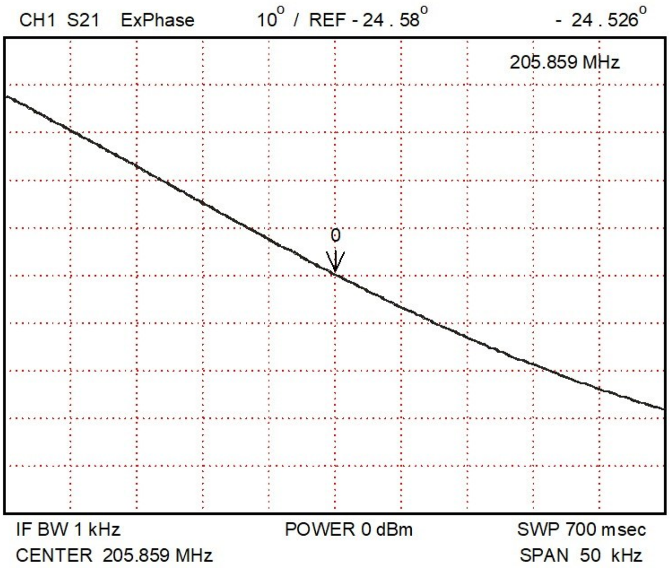


Fig. 13. Characteristics of the S_{21} phase of the SAW sensors in the vicinity of the oscillation frequency for sensor SAW2.

V. CONCLUSIONS

The paper shows a new approach to oscillators utilized together with dual delay line SAW gas sensors upon a test set operating at frequency 205MHz. The novelty is adoption of an oscillator sharing common broadband active transducer between two delay lines forming DMMP detection network and adjust oscillation conditions by means of a precise multi-state phase shifter. Proposed electronic circuit offers small sensitivity to ambient temperature that is about 10 time better than obtained in common test sets built of two separated oscillators which was proved experimentally.

The alternate SAW lines operation additionally eliminates issues connected with interference occurring in separated oscillators cooperating with dual delay lines fabricated on common substrate.

In terms of complexity, the test set is comparable to commonly used networks.

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