XIX IMEKO World Congress
Fundamental and Applied Metrology
September 6−11, 2009, Lisbon, Portugal

COMPARATIVE INVESTIGATIONS OF TWO KIND OF ELECTRONIC CIRCUITS FOR MULTICHANNEL SAW-BASED GAS SENSORS

Henryk Urzędniczok

Silesian University of Technology, Institute for Measurement, Electronics and Control, Gliwice, Poland, henryk.urzedniczok@polsl.pl

Abstract − Gas sensors based on surface acoustic wave transducer equipped with two types of primary electronic circuit, oscillatory circuit and a circuit of phase shift detection, are described. Modal character of oscillatory circuit is analyzed, and consequence of this fact are discussed. Results of investigations for this type of circuit are presented. A conception of SAW transducer with phase shift detection is proposed, a simple electronic circuit for this method is described and results of investigations are presented.

Keywords gas sensor, conditioning circuit, surface acoustic wave

1. SAW TRANSDUCER AS A GAS SENSOR

Systems with surface acoustic wave (SAW) have been applied in the construction of gas detectors for a long time [1-4]. The SAW gas sensors are composed of at least one acoustic delay line with a sensitive thin film layer on a top of the piezoelectric substrate and a pair of interdigital transducers (IDT) for excitation and detection of Rayleigh wave (see Fig. 1).

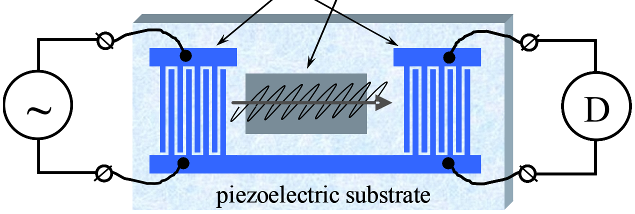

Fig. 1. Structure of SAW-based gas sensor

Interaction between specific gas molecules and the sensitive layer causes changing of wave propagation properties – damping of the wave and its velocity. In consequence the relation output to input signal changes enough to detect the presence or to measure concentration of the gas in atmosphere around the sensor. A proper primary electronic circuit (conditioning circuit) is necessary to convert changes of wave propagation in SAW transducer into an electric signal useful for measurement purpose.

In this paper results of investigations of two types of primary electronic circuits are presented and discussed. The first one is the oscillator with frequency output signal and the second is the phase-shift output circuit.

2. FREQUENCY OUTPUT CONDITIONING CIRCIUT

As a conditioning circuit for SAW sensors the electronic oscillators are often applied – the delay line with SAW transducer is placed in the feedback loop of an amplifier. The acoustic delay line ensures the phase condition for oscillation, whilst the amplifier ensures the amplitude condition. The main disadvantages of this simple configuration are high output frequency range (30 – 150 MHz) and a weak thermal stability. Therefore a much more suitable configuration in practical applications is the dual delay line design with the active and the reference acoustic paths, as shown in Fig. 2.

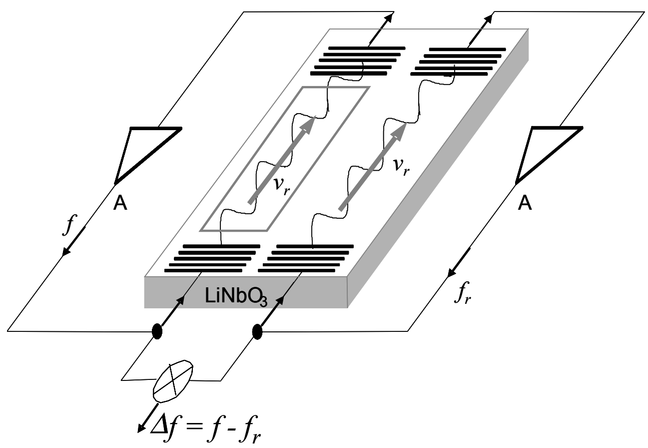

Fig. 2. SAW-based gas sensor with active and reference paths

Both delay lines are placed in the feedback loop of oscillator circuits. The influence of gas on the active path is detected as a change of the differential frequency Δf, which is obtained on the output of electronic mixer circuit. In such configuration the frequency of output signal is reduced by an electronic mixer to the low frequency range - usually the differential frequency is in the range of 10–500 kHz. In addition the thermal stability is considerably improved due to the second free path, which serves as a reference and therefore compensate influence of temperature and pressure.

The changes of differential frequency are relatively small (typically in range from 500 Hz to 5 kHz), but detection of frequency changes in this range, when the base frequency is on level up to 500 kHz is not difficult, so the accuracy of the gas detecting system seems to be satisfied.

The two channel gas sensor equipped with a SAW transducers and a conditioning circuit shown in Fig. 3 was build and investigated.

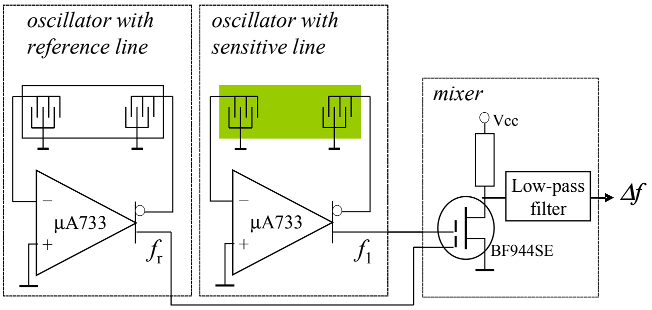

Fig. 3. Oscillator as a primary electronics circuit for SAW sensor

It is possible to build multi-channel gas sensor, when two or more path with sensitive layers are placed (see Fig. 4b). An adequate number of oscillators and mixers are necessary in this case.

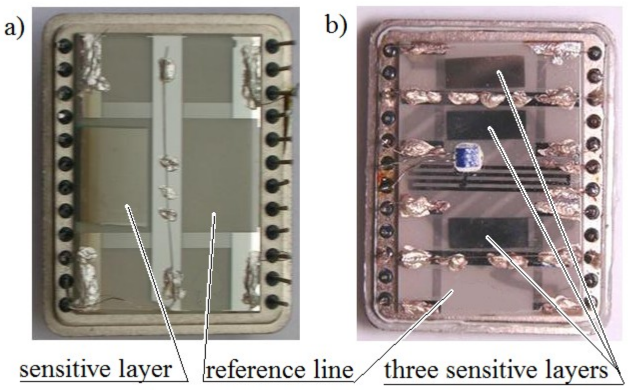

Fig. 4. One channel (a) and three channel (b) SAW gas sensor

The one- and three-channel sensor was investigated and results was published earlier [e.g.5,6]. An example of observed methane influence is presented in Fig. 5. The third layer composed of 90nm M_2O_3 and 14 nm Pd is the most sensitive ones and the first layer (60 nmV_2O_5 and 14 nm Pd) is hardly sensitive. As other experiments shows the first layer is much more sensitive for hydrogen. This behavior allows to conclude, that it is possible to build multi-channel SAW gas sensor sensitive for mixture of gases.

The influence of gas concentrations onto the frequency of output signal forms the main characteristic of this sensor. In this paper, however, other properties of such sensor are intended to discuss. The most important in practice is the instability of output signals due to the temperature influence and long time drift effects [7], but there are some additional problems not discussed in the paper.

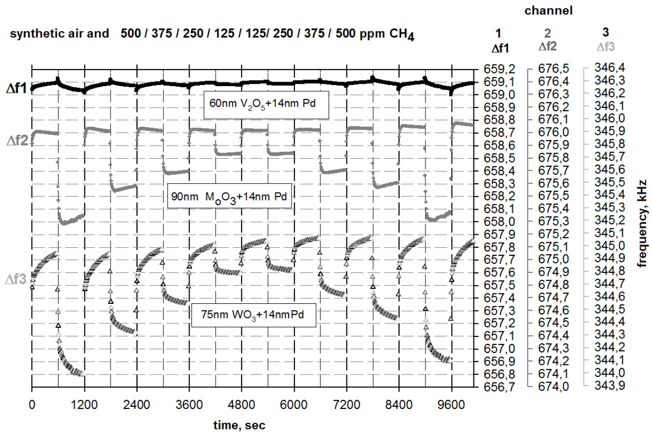

Fig. 5. Changes of output frequencies for different concentrations of methane (three channel SAW sensor with different sensitive layers)

2.1 Modal characteristics of a SAW oscillator

An additional, very inconvenient, effect was observed – frequency of the excited oscillations is not always the same after switch on the power supply, in spite of the same gas concentrations, temperature, etc. Explanation of such behavior lies in specific property of the SAW-based transducer in oscillatory circuit, namely, its modal character, like shown in Fig. 6.

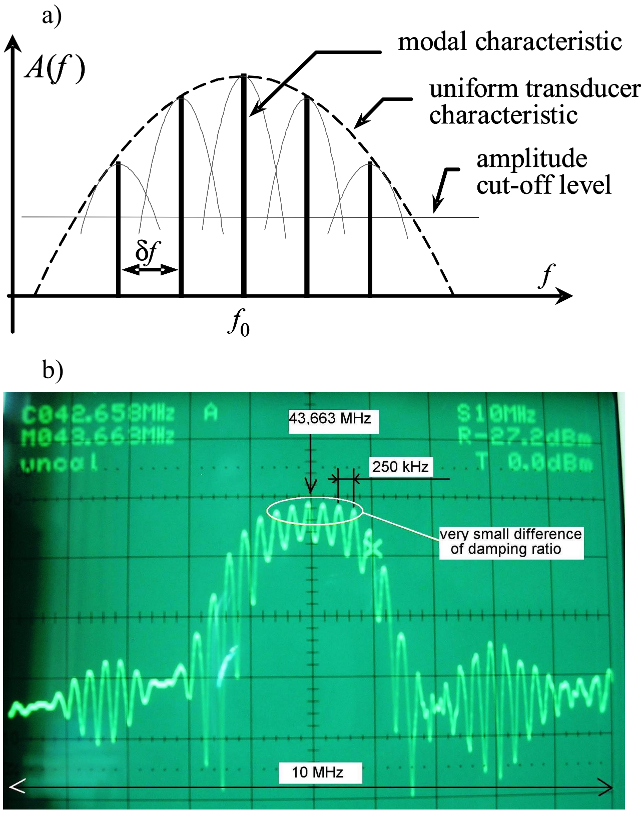

Fig. 6. The theoretical and the measured modal characteristic of SAW oscillator

A detailed analysis of the modal characteristics of a single delay line is to be found in reference [3]. Shortly it can be explained by the analyze of the phase condition of oscillation. The frequency of oscillation in the case of a single delay line is determined by the phase condition formula:

$$\frac{2\pi f_n L}{v_0} + \varphi_A + \varphi_{SAW} = 2\pi n \qquad (1)$$

Where: φ_{SAW}, φ_A – are phase shifts in the SAW line and amplifier, respectively; L – is the length of the delay line (distance between the central points of the IDT transducers), f_n - is the oscillation frequency and n=..,-2,-1,0,1,2,.. denotes the particular oscillation modes.

The phase shift in an external circuit (two IDTs and amplifier) is constant and usually considerably less than the phase shift in the acoustic line - this is especially true at large value of L in comparison to the wavelength. At λ=80μm the distance of L=10 mm contains 125 waves. As a consequence we have a series of modal frequencies f_n which approximately satisfies the phase condition of oscillation:

$$f_n = n\frac{v_0}{L}\ . \qquad (2)$$

The distance between two next modal frequencies is equal to:

$$\delta f = f_n - f_{n-1} = \frac{v_0}{L}\ . \qquad (3)$$

That all becomes much more complicated when two acoustic paths are applied, and in one of them a thin active layer is created in order to achieve a differential structure. The velocity of the surface wave propagation v_0 is then slightly decreasing for each frequency mode. As a result the whole modal characteristic (the red one in Fig. 7) is shifted in the direction of lower frequencies and the distance between two modal frequencies becomes smaller.

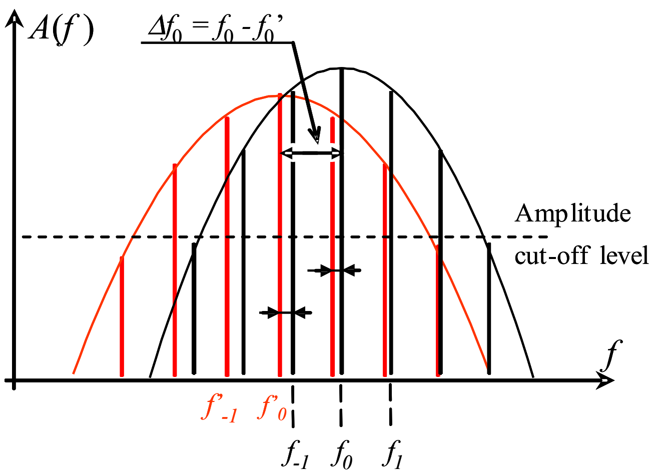

Fig. 7. Modal characteristics of two SAW oscillators

Such modal character of transducer is very inconvenient when an electronic circuit for gas sensor based of dual-line (or multi-line) SAW transducer have to be designed. The amplitude and phase condition of oscillation are usually fulfilled for few modal frequencies for each of the two SAW transducers. To obtain exactly the main frequency f_0 the amplitude cut-off level should be tuned very precise in each channel, because the damping characteristic is rather flat around the main frequency (see Fig. 6b). In addition its time- and thermal stability should be very high. In practice the frequency, which is actually obtained, depends on accidental conditions during process of excitation of oscillations (e.g. when power supply is turned on). This causes, that instead the main differential frequency $\Delta f_0 = f_0 - f_0'$, it is possible to obtain a few another values of differential frequencies (eg. $\Delta f = f_0 - f_1'$ or $\Delta f = f_1 - f_0'$, etc.). Values of differential frequency becomes quite different, in spite of the gas concentration and other factors are still nearly the same (!). Exemplify results, obtained when the power supply was turned on for many times, are shown in table 1.

Table 1. Practically observed modal frequencies – dual delay line configuration

Differential frequency Δf [kHz]	Measuring frequency f_0 [kHz]	Reference frequency f_1 [kHz]
19	43 441	43 460
209	43 838	43 629
90	43 299	43 389
318	43 071	43 389
559	43 094	43 653
57	43 934	43 877
102	43 116	43 218
138	43 183	43 045
374	43 183	42 809

In each case the frequency is weakly influent by the temperature, so thermal stabilization is necessary [7].

The effect described above isn't very inconvenient when the sensor is under laboratory investigation, e.g. for testing of the different sensitive layer materials – in this case only changes of the actually obtained differential frequency Δf during the experiment are important and it may be easy to determine. However, in practical application such behavior is unacceptable. In this case the obtained value of differential frequency has to be converted into displayed gas concentration in a clear-cut mode.

To solve that a problem various electronic oscillator circuits have been proposed, sometimes very complicated and unpractical [8]. One of the simplest way to ensure excitation at the same frequency every time the power is turned on, depends on the proper (slow enough) raising of the supply voltage for each of the oscillator circuits. This method is described in [9]. Unfortunately further investigations shows, that frequency of output signal may accidentally change rapidly, when the temperature changes too much (see. Fig. 7). This may appear because frequency of one of the oscillators changes to the next modal value. Extremely efficient stabilization of sensor temperature is strongly recommended in that case [6].

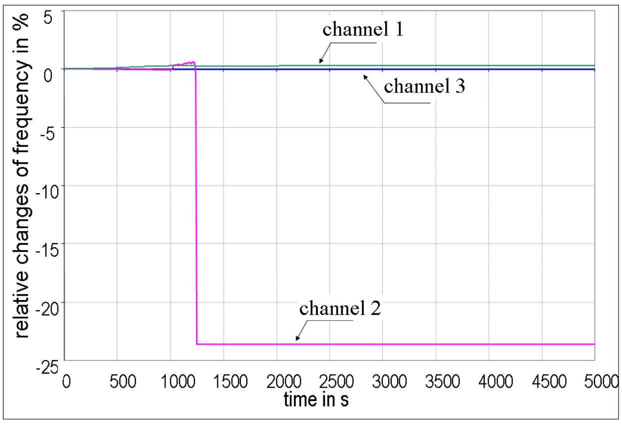

Fig. 7. Example of rapid frequency change [6]

3. PHASE-SHIFT BASED CONDITIONING CIRCUIT

Another conception of primary electronic circuit for SAW based gas sensor is proposed as a solution of the problems caused by modal character of the SAW transducer in oscillatory circuit. When the SAW-transducer works in circuit without feedback loop, the modal character practically not exist. Only due to edge reflection of Rayleigh wave in the piezoelectric substrate, a weak modal effect may be observed. The IDT has to be excited from the external signal source of constant frequency, best equal to the main frequency f_0. Basic idea of that circuit in two versions is shown in Fig. 8.

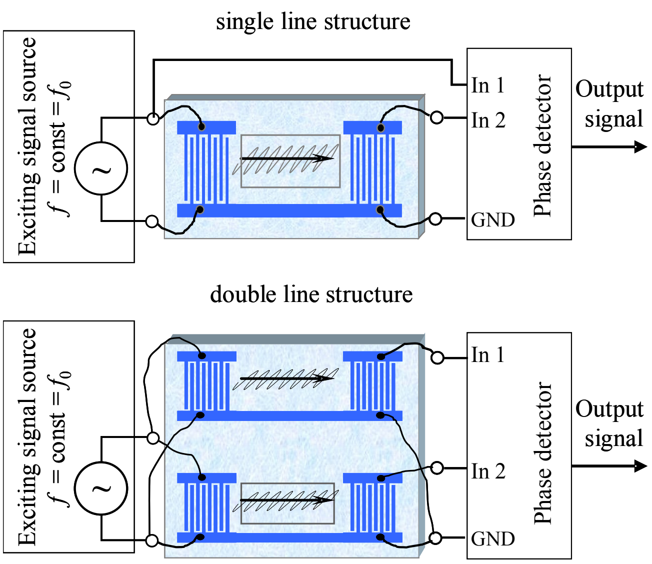

Fig. 8. Principle of operation of the phase-shift based SAW gas sensor in single and double line versions

In order to decrease influence of temperature, the differential structure of SAW gas sensor with phase-shift-converter is used in the same manner as for the frequency output conversion method. This is easy to realize using two SAW transducers, one with the sensitive layer and the second without layer as a reference one. In this case instead of the exciting signal, the output signal of the reference SAW transducer is connected to the input 1 of phase detector.

Due to the properties of the SAW transducer, the phase shift between the exciting and the output signals depends on parameters of acoustic delay line and therefore on the gas concentration, too. This phase shift is measured in single line structure. When two line structure is used the difference $\Delta\varphi$ between two phase shifts are measured. It is described by following formulas:

$$\varphi_1 = \frac{2\pi f L_1}{v_1}; \quad \varphi_2 = \frac{2\pi f L_2}{v_2}; \quad \Delta\varphi = \varphi_1 - \varphi_2 \tag{4}$$

where L_1 and $L_2 \approx L_1$ are the distances of wave propagation from exciting to receiving IDTs, v_1=const. and v_2=variab. are velocities of wave propagation in reference line and the line with sensitive layer, respectively, and f is frequency of exciting signal.

The phase shift for the single period of wave propagated in the acoustic delay line is very small. However, the distance between the exciting and receiving IDTs is usually equal to hundreds of wave length, so the total phase shift is enough to measure or convert into voltage signal.

As a phase detector ("phase-shift to voltage" converter) a very simple electronic circuit, shown in Fig. 9, is proposed. The principle of operation is explain in Fig. 10. The average value of output voltage is proportional to the phase shift between signals on inputs In1 and In2.

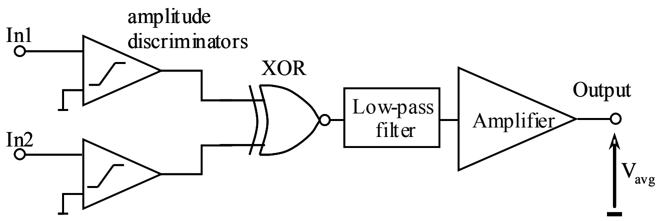

Fig. 9. Basic diagram of electronic circuit of the phase-to-voltage converter

In practice an differential amplifier of high amplification factor (e.g. 100) should be applied at the end of the conditioning circuit. This is caused by relatively small phase shift changes (on the level of 5 degree) and existing of initial phase shift caused by asymmetry of the two lines. Good stability of exciting signal frequency is essential in this case, because the distance of wave propagation form exciting to receiving IDTs is constant and therefore phase shift is proportional to the frequency. By applying of the dual line structure, the influence of frequency changes may be strongly reduced, but not totally eliminated.

Investigations of proposed phase-shift conditioning circuit were carried on. The dual line SAW sensor was used, with sensitive layer composed of 80 nm H_2Pc (metal-free phtalocyanine) and 20 nm Pd [5]. As an exciting source the Fluke 6071A type RF generator, of precise controlled and stable frequency of output signal was used. Diagram in Fig.

11 shows, that average value of output voltage depends on gas concentration, hydrogen in this case.

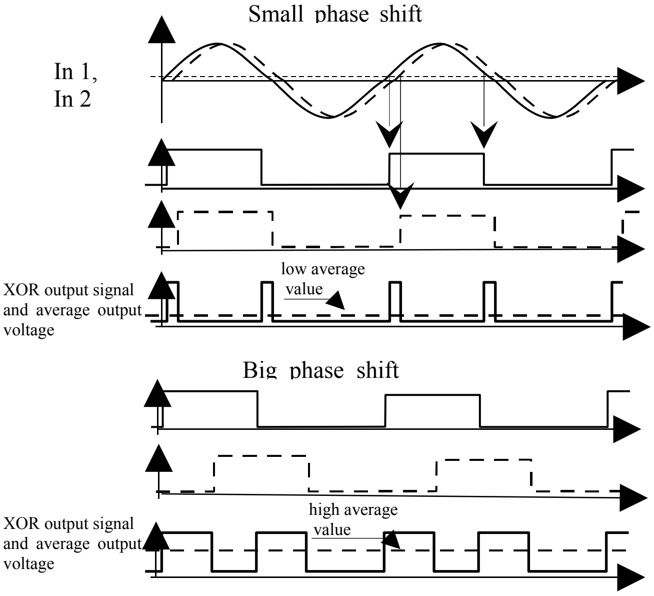

Fig. 10. Diagram of signals in phase-to-voltage converter shown in Fig.9.

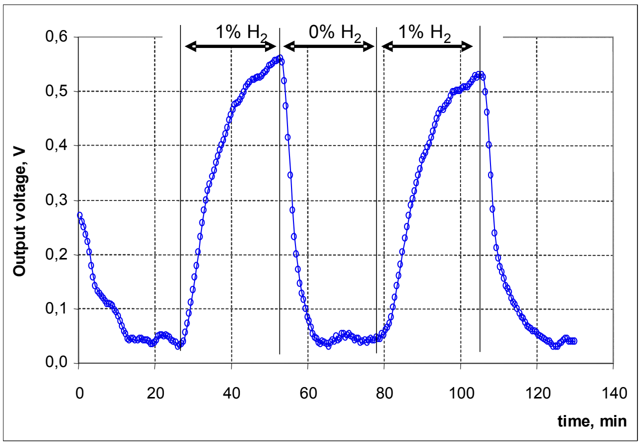

Fig. 11. Changes of output voltage for different concentrations of hydrogen (one channel SAW sensor with phase output conditioning circuit))

4. CONCLUSIONS

Both of presented above conception of conditioning circuit for SAW based gas sensor are simple and suitable. Output signal of the oscillatory circuit is on high level and measuring of its frequency is simple and precise. Unfortunately, this circuit has one, but very inconvenient disadvantage – due to its modal characteristic, the actual differential frequency of excited oscillations may be accidental. A special method of excitation ought to be applied, to ensure the obtained differential frequency on the same level for the same gas concentrations.

The phase-shift circuit don't show such disadvantage. The level of its output signal is small and therefore an differential amplifier ought to be applied. In this case an external source of excitation signal is necessary. Frequency of this signal ought to be stable. Nowadays such an oscillator may be easy build using commercial ICs, e.g. ADF4108BCPZ, Analog Devices.

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Acknowledgements

The investigations described in this paper was granted by Polish Ministry of Science and Higher Education, grant no. R01 03901.