Overtone Oscillator for SAW Gas Detectors

Mateusz Pasternak

***Abstract*—A design of an overtone oscillator a with surface-acoustic-wave (SAW) resonator is described in this paper. The circuit works stably on the frequency 4.710 GHz (29th harmonic of loaded resonator) at about the -2 dBm level. In the construction, distributed-constant circuits have been applied. Commercially available SAW sensors usually work within the range of frequency from a few dozen to a few hundred megahertz. On the other hand, it is a well-known fact that the mass sensitivity of such devices is directly proportional to the square of its operating frequency, and SAW sensors for organic vapors, for instance, are usually mass sensitive. For this reason, an increase in the SAW sensors' operating frequency seems to be useful. The circuit described in this paper shows the possibility of a dramatic rise in SAW operating frequency by exerting its operation through a specific high overtone (harmonic frequency) of the SAW resonator. The overtone frequency in such a solution then plays the role of basic mode. The oscillator proposed in this paper seems to be a good tool for chemisensitive-SAW-coating investigation.**

***Index Terms*—Microwave surface-acoustic-wave (SAW) stabilized oscillators, SAW sensors.**

I. Introduction

IN ORDER TO comply with regulations for air pollution for industrial processes, public institutions, and private households, new low-cost reliable gas sensors, as well as their arrays (so-called e-noses), have been in demand.

Piezoelectric sensors for chemical agents and electronic-noses applications are frequently based on surface-acoustic-wave (SAW) resonators. They are also useful in the detection of biological agents if a sensitive surface is activated with the right antigen [1], [2].

SAW devices have many advantages: They are relatively technologically simple; they are low cost; and they also have very small dimensions (usually decreasing with operating frequency). Moreover, the sensors, based on SAW devices, are sensitive enough, but for application with high-performance requirements (like toxic gases, drugs, or explosives), sensitivity has to be higher. Although, in the sensor designs, the most important are the chemisensitive layers (or surface only in, e.g., Z-noses applications), the sensitivity of the whole instrument is also influenced by the electronic part.

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The author is with the Institute of Radioelectronics, Military University of Technology, 00-908 Warsaw, Poland (e-mail: mateusz@wel.wat.edu.pl).

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Results of both theoretical and experimental research [3], [4] show that the mass sensitivity of the SAW chemical sensors is directly proportional to the square of operating frequency

$$S_m = -\nu_{\mathrm{P}}\pi^2 f^2 \left\{1 - 4\frac{C_{\mathrm{S}}^2}{\nu_{\mathrm{P}}^2}\left(1 - \frac{C_{\mathrm{S}}^2}{C_{\mathrm{P}}^2}\right)u_x^2 + \left(1 - \frac{C_{\mathrm{S}}^2}{\nu_{\mathrm{P}}^2}\right)u_y^2 + u_z^2\right\}$$

where ν_{P} is the phase velocity of the wave mode, C_{P} and C_{S} are the bulk compression and shear waves speeds in the chemisensitive layer, respectively, and $\boldsymbol{u}$ are the displacements on the surface of the substrate.

The film interacts with the substrate both electrically and mechanically, but for many polymer films, developed for complex-gases detection, the mechanical interactions are much stronger, and the electrical influences can be neglected.

Unfortunately, an advantageous mass sensitivity–frequency dependence is rather hard to apply because in the SAW sensor, the dimensions of a resonator and, thereby, the area of the chemisensitive film, usually decrease with the operating frequency. An increase in frequency, however, is profitable but the area decrease of the film is not. The smallest area of the chemisensitive film placed on the acoustic channel, the smallest amount of detecting gas particles sorbed, and the weakest change of mechanical loading of the SAW substrate are all obvious. To avoid the problem, the use of higher harmonics seems to be reasonable. In this case, it can be possible to apply SAW devices with relatively extensive active area and simultaneously high-operating frequency. A suitable size of the chemisensitive area is also important from layers-deposit technology's point of view, because in many cases, it is necessary to provide a very high precision of layer location (much easier on more extensive areas). Such precision is needed in order to place the chemisensitive layer exactly between interdigital transducers. It is important because SAW-resonator reflectors should remain free of external load, which may distort their scattering parameters and make the important resonators' characteristics worse.

It is necessary to stress that such SAW devices work analogically to the Fabry–Pérot resonators and always generate overtones. Usually, developers of SAW resonators and SAW stabilized oscillators tend to supress higher harmonics as undesirable frequencies in order to focus all of the energy from surface vibrations close to the basic frequency. In the majority of cases, such tendency is legitimate, but the excitation of harmonics may be useful from the SAW sensors' point of view. Using distributed-constant circuits, it is possible to construct the oscillator that sustains SAW vibrations on chosen overtone only. In this case, it plays the role of basic frequency.

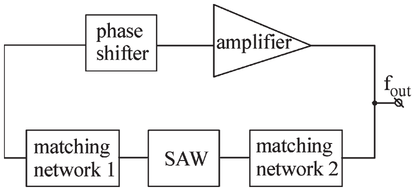

Fig. 1. General structure of SAW oscillator.

II. BASIC PRINCIPLES

Although it is possible to construct the SAW stabilized oscillator using the negative-resistance approach, the SAW chemical sensors usually operate in the positive-feedback loop of an amplifier (see Fig. 1) [5].

The matching networks control the match of the input and output impedances of the SAW resonator to the input and output impedance of the amplifier, respectively. The phase shifter is necessary to provide a proper phase shift in the loop. It is important that the operating frequency of the feedback-loop SAW stabilized oscillator should be much more dependent on the phase shift of the loop than the center frequency of SAW resonator. Actually, the feedback-loop oscillator may operate on the sloped part of SAW-amplitude characteristic if the phase shift around the loop is inaccurately tuned or drifting with the ambient parameter changes. For this reason, the phase shift of the loop stability determines the most important oscillator parameters and, thereby, frequency stability.

Generally, the bandwidth of the resonator depends on its source and the load impedances. An increase in the impedance raises the bandwidth and reduces the Q-factor of the resonator. Wider bandwidth makes it possible to trim the resonant frequency slightly, but it results in a lower frequency stability and sensitivity to the temperature fluctuations. It also causes an increase in the oscillator components' tolerances.

If the oscillation conditions are fulfilled (the total gain in the loop must be greater than one, and the total phase is equal to $n \cdot 360°$), oscillations begin to generate an output frequency related to the surface of SAW-propagation properties with changes being the result of surface interactions with the environment. Interactions (in this case the mass load) cause a measurable frequency shift that is proportional to the operating frequency and the film area. For this reason, one can achieve a desirable frequency increase without a significant decrease in the sensitive film area.

The main problem is the construction of the matching networks and the phase shifter operating properly in the microwave-frequency range. For low frequencies, the needed networks employ the lumped components.

For high frequencies, one can use the distributed-constant instead of the lumped-constant circuits. Such an approach can significantly reduce the components' number and contributes to an increase in circuit stability. Moreover, the distributed-constant circuits require a simple planar technology, which may result in lower costs.

Both matching networks and phase shifter might be manufactured in a simple way by means of microstrip lines of a suitable length. They can transform input impedances to the required output values and simultaneously provide an essential phase shift (see Fig. 2).

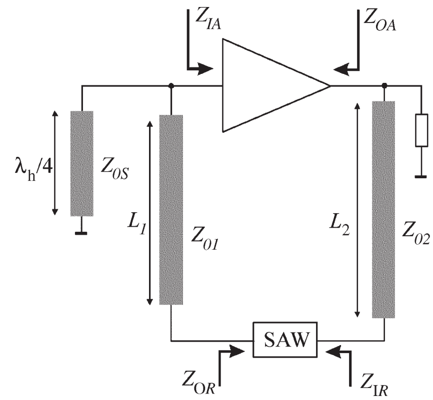

Fig. 2. General structure of SAW oscillator with distributed constant elements. Z_{IA}, Z_{OA}: input and output impedances of the amplifier. Z_{IR}, Z_{OR}: input and output impedances of SAW resonator. Z_{01}, Z_{02}: characteristic impedances of microstrip lines with L_1 and L_2 lengths, respectively. $Z_{0\mathrm{S}}$: characteristic impedance of the stub. λ_{h}: electromagnetic wave length corresponds with the operating frequency.

The microstrip-line technology also allows us to use specific circuits that are well known microwave techniques, like stubs, splitters, isolators, etc. Such an approach gives a possibility to control the circuit at the electromagnetic-wave-length level. To design the SAW oscillator with microstrip lines, one only needs to design its length and width. The parameters are relatively easy to obtain from the well-known solution of the telegraph equation, microstrip-line-design formulas, and knowledge of the amplifier and SAW-resonator-phase characteristics. They may be determined by the solution of following system:

$$\left.\begin{aligned} Z_{\mathrm{OA}}(f_{\mathrm{h}}) &= Z_{02}\tfrac{Z_{\mathrm{R}}(f_{\mathrm{h}})+jZ_{02}\tan\beta(f_{\mathrm{h}})L_2}{Z_{02}+jZ_{\mathrm{R}}(f_{\mathrm{h}})\tan\beta(f_{\mathrm{h}})L_2} \\ Z_{\mathrm{R}}(f_{\mathrm{h}}) &= Z_{01}\tfrac{Z_{\mathrm{IA}}(f_{\mathrm{h}})+jZ_{01}\tan\beta(f_{\mathrm{h}})L_1}{Z_{01}+jZ_{\mathrm{IA}}(f_{\mathrm{h}})\tan\beta(f_{\mathrm{h}})L_1} \\ \varphi_A(f_{\mathrm{h}})+\varphi(L_2,f_{\mathrm{h}})+\varphi_{\mathrm{R}}(f_{\mathrm{h}})+\varphi(L_1,f_{\mathrm{h}}) &= n\cdot 360° \\ G_L(f_{\mathrm{h}}) &> 1 \\ Z_{\mathrm{S}}(f_{\mathrm{h}}) &\gg 0 \end{aligned}\right\}$$

where index h is the harmonic number, $\beta = 2\pi/\lambda_{\mathrm{h}}$, $\varphi_A(f_{\mathrm{h}})$ is the phase shift of the amplifier at frequency f_{h}, $\varphi(L_1, f_{\mathrm{h}})$ is the phase shift of the microstrip line with the length L_1, $\varphi(L_2, f_{\mathrm{h}})$ is the phase shift of microstrip lines with the length L_2, $\varphi_{\mathrm{R}}(f_{\mathrm{h}})$ is the resonator phase shift, $G_L(f_{\mathrm{h}})$ gain of the amplifier, and Z_{S} the short-circuited stub impedance introduced into the loop, $j = \sqrt{-1}$.

The lossless microstrip lines in the above system, and the same input and output impedances of resonator are assumed. The first and second equations describe the impedance transformation from the amplifier output to the resonator input and from resonator output to amplifier input, respectively. The next equations describe phase and amplitude conditions, and the last one describes the short-circuited stub impedance introduced to amplifier input. If the stub has arbitrary $\lambda_{\mathrm{h}}/4$ length (as in Fig. 2), the last condition of the system will be fulfilled automatically.

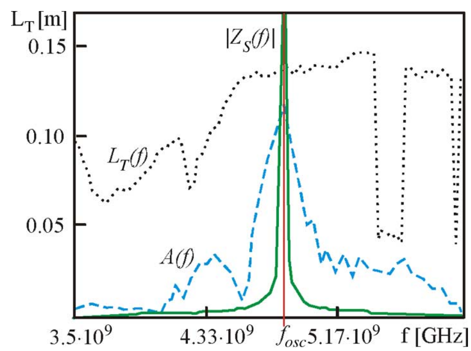

Fig. 3. Oscillation conditions diagram. $A(f)$ is the amplification surplus (over one), $L_T(f)$ total microstrip-lines' length fulfilling the phase condition, $|Z_S(f)|$ impedance of $\lambda_h/4$ short-circuited stub introduced to the loop. The characteristics are normalized for the values on the ordinate mean (for the dotted curve) and the total (and minimal) microstrip-lines' length.

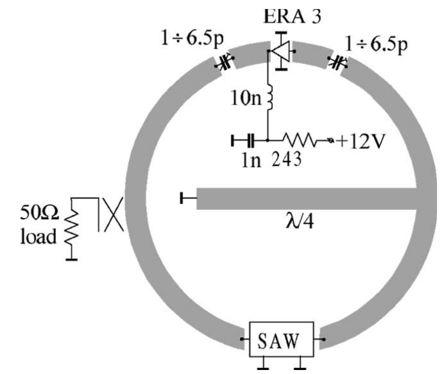

Fig. 4. Electric scheme of oscillator.

Characteristic impedances of microstrip lines can be calculated using the following semiempirical formula [6]:

$$Z_0 = 337\frac{h}{w}\left\{\sqrt{\varepsilon_r}w\left[1+1,735\varepsilon_r^{-0,0724}\left(\frac{w}{h}\right)^{-0,386}\right]\right\}^{-1}$$

where h is the thickness of the laminate, ε_r its permittivity, and the w microstrip-line width.

The minimal total equivalent length of the loop, taking into account the sum of the amplifier, resonator, and microstrip-lines' phase shifts, is equal to the electromagnetic wave length λ_h.

The above algebraic system can be solved analytically if both amplifier and resonator amplitude and phase characteristics are known. The system has nontrivial solution, which may be drawn as shown in Fig. 3.

The above diagram shows that oscillations are possible at the frequency determined not only by fulfilling phase and amplitude oscillation conditions but also by the stub impedance. The stub with $\lambda_h/4$ length is introduced into the amplifier input low impedance (practically short circuit, far from desired harmonic). For this reason, the short-circuited stub adds a third oscillation condition and allows the rise of the oscillations on frequency corresponding to $n \cdot \lambda/4$ only. The maximum operational frequency in such an oscillator is limited by the SAW resonator harmonics' amplitudes (signal/noise ratio) and bandwidth of the amplifier applied.

III. Application Example

To check the main properties of the circuit presented in Fig. 2, several prototypes have been made. Each of them was preliminarily simulated in the Eagleware environment. They work stably, but it is necessary to use a temperature-stable microstrip-line substrate (laminate), the best one having high permittivity and homogeneity; otherwise, the geometry of the circuit might be too extensive, and the oscillator temperature will be unstable.

The example presented below is a half of the double oscillator in a compensated differential circuit working on the 29th harmonics of 167.71 MHz of a two-port pseudosurface-wave resonator RS 1641 KP type made at the Institute of Electronic Materials Technology, Warsaw [7]. The oscillator works stably with the other SAW resonators (of course the loop for each of them have to be calculated separately). The exemplary oscillator was built as a λ-length asymmetric microstrip ring instead of the microstrip-line sections (amplifier and resonator phase shifts are taken into consideration) with a $\lambda_h/4$ short-circuited stub that is halfway to the input of the amplifier. The configuration allows us to keep electrical connections between elements as short as possible. The stub is not seen by the ring for waves of length $n \cdot \lambda_h$ only (makes the circuit open). For the other harmonics, it introduces a low impedance into the ring and significantly brings the signal magnitude down. In this way, the standing electromagnetic waves arise in the ring with the frequency determined by the SAW resonator and the distributed-constant-circuit geometry (see Fig. 4).

The input and output resistance of both amplifier and resonator are equal to 50 Ω, and the same value has the characteristic impedance of the microstrip ring that matches the input and output reactances.

If the amplifier characteristic is sharp enough at the end of its band, the ring will operate with one harmonic only. Low magnitude of such a harmonic is amplified in the circuit to the level required by the load (most frequently, mixer).

In this case, the ERA3 microwave chip has been applied as an amplifier. It has a wide bandwidth (from dc to 6 GHz) and a high gain (22 dB at 1 GHz) and requires a small number of external components. To achieve desired amplifier characteristic, the coupling capacitors were replaced with trimers. It is very important to provide an appropriate high-electromagnetic screening level and, in the case of several oscillators' cooperation, a high-level power supply isolation. The trimming of the oscillator consists of tuning the trimers' capacitance and the stub's length. The loop trimming is also possible by extending the ring using a directional coupler with varactor loading.

A working model (see Fig. 5) has been made by the QC 5000 engraving machine.

The model was made using a laminate with $\varepsilon = 2.5$, but oscillators on the ceramic laminates (with high-ε value) could be much smaller (e.g., laminate Reynolds TMM 10).

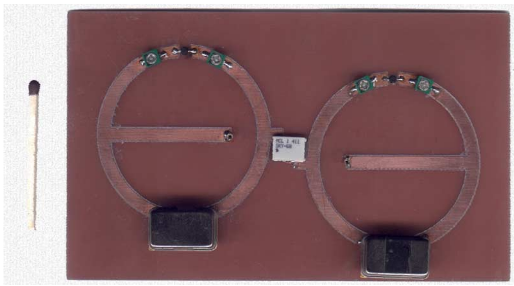

Fig. 5. Photograph of the double oscillator. Both rings are loaded by inputs of double balanced mixer. Low-frequency output is located on the reverse side of the laminate.

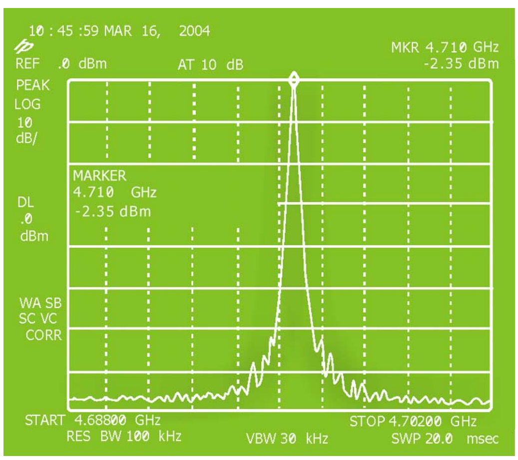

Fig. 6. Screenshot from the spectrum analyzer (harmonic generated by the circuit from Fig. 4).

IV. Results of Measurements

The oscillator with the SAW resonator (without a sensitive layer) was investigated by means of an HP-8593E spectrum analyzer and a TED-10-CM digital-frequency meter. It works stably on the frequency 4.710 GHz (29th harmonic of loaded resonator) at the level of about -2 dBm. The other harmonics are suppressed below the -30 dBm level (see Fig. 6).

The frequency generated was almost insensitive to the power-supply fluctuation in the range of about ± 2 V, but of course the signal magnitude during the power-supply variation was changing because the phase and magnitude characteristics were generally dependent on the power supply. Dependence of the frequency stability on the power supply is determined mainly by the amplifier; hence, the power supply has to be sufficiently stabilized.

Root Allan variance (a statistical measure of the stability of an oscillator [8]) was determined mainly by the SAW resonator applied and loop properties and reached $\sim 10^{-11}/100$ s at room temperature. It seems to be good enough for the oscillator application in SAW sensor technology.

Due to the microstrip-line-ring application, the oscillator is sensitive to external electromagnetic fields. For this reason, it has to be screened very well.

The oscillator was also investigated using different thick chemisensitive layers and different test gases [9]. An exemplary

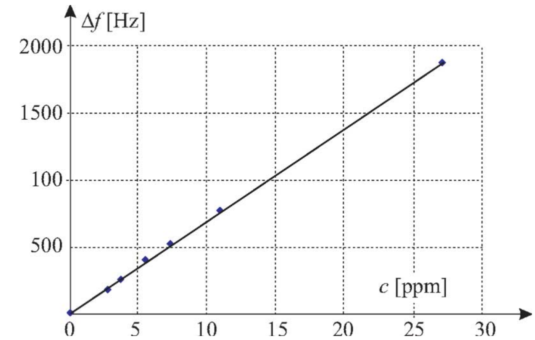

Fig. 7. Frequency change versus concentration of DMMP at 30 °C in the oscillator with a poly(3-cyanopropyl)siloxane layer.

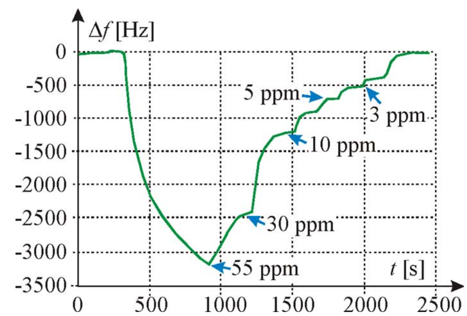

Fig. 8. Time response of the exemplary sensor. Arrows indicate the test gas concentration at 30 °C.

result for frequency changes versus concentration of dimethyl-methyl-phosphonate (DMMP) at 30 °C in the oscillator, with a poly(3-cyanopropyl)siloxane acoustically thick layer shown in Fig. 7.

The sensors work fast. The frequency change on the order of 2 kHz, was achieved in 500 s. The time response for the above layer and test gas at 30 °C is shown in Fig. 8.

The poly(3-cyanopropyl)siloxane acoustically thick layer also has good selectivity. Sensitivity of the exemplary sensor obtained for hexane was about 1 Hz/100 ppm.

V. Conclusion

The application of distributed-constant circuits makes it possible to manufacture a simple high-frequency SAW stabilized oscillator working on a chosen harmonic. The frequency of operation is restricted from the lower values by the circuit geometry that should not be too extensive (especially for commercial applications) and from the upper values by a chosen harmonic level, amplifier gain, and phase noises in the feedback loop.

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Mateusz Pasternak was born in Wadowice, Poland, in 1965. He received the M.S. degree in electronics from the Department of Electronics, Military University of Technology (MUT), Warsaw, Poland, in 1989 and the Ph.D. degree from the Institute of Applied Physics, MUT, in July 1995.

He joined the Acoustoelectronics Faculty at the Institute of Applied Physics while working toward the Ph.D. degree. Initially, he started his research activity from theoretical analysis of mechanical and coupled-field properties of crystalline surfaces in various solids in different conditions, emphasizing the role of impurity defects, and other point irregularities. It was consistently extended to application works in theory and construction of surface-acoustic-wave (SAW) devices realizing diverse signal processing functions. His basic achievements are mostly related with developing of tractable techniques for treating the surface distortion-related phenomena, both statical and dynamical ones, within a consistent uniform framework of nonlocal modeling. The comprehensive study of surface-wave propagation and scattering properties was completed with a design and manufacture of a variety of advanced SAW devices like special high-frequency SAW filters and convolvers and making use of impurity-stimulated instability to promote a new solution for SAW devices with variable characteristics. He is currently an Associate Professor with the Institute of Radioelectronics, MUT. His research interests involve the design of SAW stable oscillators and their applications in communication and sensor systems. He has published a total of 34 scientific and technical papers. He is the holder of one patent.