Synchronization in the system of coupled oscillators based on VO$_2$ switches

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Abstract. VO$_2$ switches with threshold voltages less than 2 V were fabricated. Synchronization between two oscillators based on VO$_2$ switches coupled through resistance and capacitance was investigated. For resistive coupling range of resistances in which synchronization appeared was defined and phase instability was observed. For capacitive coupling two synchronization modes were found. Simulation of changing of the relative phase for two oscillators in the case of capacitive coupling for both synchronization modes has been carried out. The relative phase variation range more than 310° was obtained.

1. Introduction
Metal-insulator transition in vanadium dioxide has been known since 70-th of the 20-th century [1]. In practice, this effect can be used in electronic oscillators, temperature and chemical sensors with frequency output. Nowadays, oscillators based on VO$_2$ switches arouse interest as elements of oscillatory neural networks (ONN) [2]. The advantages of these ONN over other solutions [3, 4] are compatibility with CMOS technology, scalability, and possibility of working in megahertz frequency range.

In this paper, with the aim of application such oscillators in the ONN we investigate synchronization effects between two oscillators based on VO$_2$ switches in case of resistive and capacitive coupling. The resistive coupling is attractive because of its compactness and possibility of tune coupling strength using MOSFET or memristor as a coupling element. On other hand, capacitive coupling is characterized by galvanic isolation between oscillators, that would provide more reliable oscillations.

As the ability to control the phase difference between oscillators is important in phase-shift keying ONN, simulation of changing of the relative phase for two oscillators has been carried out.

2. Sample preparation and characterization
The planar switches structures were formed on r-cut sapphire substrate by magnetron reactive sputtering of vanadium in Ar and O$_2$ atmosphere in ratio Ar/O$_2$=7/1 at room temperature, total pressure was 5 mTorr, DC power was set to 200 W. Annealing of obtained films was carried out in O$_2$ atmosphere at temperature of 480°C and pressure of 10 mTorr for 40-60 minutes. V/Au pads were formed by optical lithography and magnetron sputtering (figure 1). All switches were located on the same substrate and VO$_2$ thin film.
The thickness of obtained films was 200 nm. Investigation of surface morphology by atomic-force microscopy showed that annealed films had grain structure. XRD analysis indicates the presence of vanadium dioxide and vanadium pentoxide phases. The resistivity temperature dependence (figure 2) showed that increasing of annealing time leads to increase in hysteresis’ loop width, transition temperature, and film resistivity both in metal and insulator state. The films which were annealed for 40 minutes were used for making VO₂ switches because they provided lower threshold voltages.

![AFM image of the switching structure.](image1)

**Figure 1.** AFM image of the switching structure.

![Resistivity versus temperature for different annealing time.](image2)

**Figure 2.** Resistivity versus temperature for different annealing time.

![Static I-V characteristic of obtained switching structure.](image3)

**Figure 3.** Static I-V characteristic of obtained switching structure.

![Dynamic I-V characteristic of obtained switching structure and developed SPICE-model.](image4)

**Figure 4.** Dynamic I-V characteristic of obtained switching structure and developed SPICE-model.

Threshold voltages of obtained switches were less than 2 V, differential resistance was about 40 Ω in the metallic state and 1,1 kΩ in the semiconductor state (figure 3). The main parameters of the obtained switches differed in less than 10%. For circuit simulation based on the measured dynamical I-V characteristics and taking into account non-linear resistance in metallic state (figure 4) the model of VO₂ switches for Ngspice simulator was developed.

3. **Experimental setup**

Oscillator consisted of the voltage supply \(V_{DD} = 82\) V, serial resistor \(R_S = 50\) kΩ, VO₂ switch and current resistor \(R_i = 10\) Ω which were connected in series. The current resistor was used to measure a
current through VO$_2$ switch. Capacitor $C = 100$ nF was connected in parallel to VO$_2$ switch and current resistor. Coupling capacitor or resistor was connected between two oscillators as shown in figure 5.

It should be noted, that besides external coupling capacitor $C_{COUP}$ or resistor $R_{EXT}$, there was coupling resistance $R_{OX} = 10$ kΩ due to the placement of switches on the common film near each other, so coupling resistance $R_{COUP}$ consisted of $R_{OX}$ and $R_{EXT}$ as shown in figure 5a. But, as will be shown in the next section, $R_{OX}$ did not affect synchronization of oscillators.

4. Results and discussion
We revealed that in the case of resistive coupling when $R_{COUP}$ was greater than 3 kΩ, synchronization did not appear, but there was a change of signal’s form and a decrease of oscillation frequency while $R_{COUP}$ was decreasing (figure 6). Synchronization took place when $R_{COUP}$ was in the range of 2-3 kΩ. However, synchronization was unstable, random phase failure caused premature triggering of one of the oscillators was occur. After failure, the phase recovered for several periods of oscillations. Decreasing $R_{COUP}$ from 2.4 kΩ to 1.9 kΩ lead to an increase of relative phase from 130° to 180° (figure 7) and a decrease of oscillations frequency from 6 to 5.2 kHz (figure 6). If $R_{COUP}$ was less than 2 kΩ then generation was unstable and after several oscillations system proceeded to state when one switch was in the metallic state and another in insulator state.

Figure 5. Equivalent circuit of coupled oscillator: a – resistive coupling; b – capacitive coupling.

Figure 6. Oscillation frequency versus coupling resistance value (Simulated).

Figure 7. Relative phase $\phi$ versus coupling resistance value (Simulated).
Figure 8. Voltage waveform of capacitively coupled oscillators ($C_{COUP}=22 \, \text{nF}$).

Figure 9. Voltage waveform of capacitively coupled oscillators ($C_{COUP}=100 \, \text{nF}$).

Figure 10. Voltage waveform of capacitively coupled oscillators ($C_{COUP}=1 \, \mu\text{F}$).

Figure 11. Oscillation frequency and relative phase $\varphi$ versus coupling capacity value (Simulated).

Figure 12. Relative phase $\varphi$ versus serial resistor $R_{S(1)}$ value ($C_{COUP}=1 \, \mu\text{F}$, $R_{S(2)} = 53 \, \text{k}\Omega$).

Figure 13. Relative phase $\varphi$ versus serial resistor $R_{S(1)}$ value ($C_{COUP}$ from 1 to 7 nF, $R_{S(2)} = 53 \, \text{k}\Omega$).
Investigation of the capacitive coupling showed that synchronization was stable and took place at the relatively small value of $C_{\text{Coup}}$ – from 3 nF. Increasing $C_{\text{Coup}}$ from 3 to 50 nF lead to increase of mutual influence between oscillators (figure 8) and to increase of relative phase from $30^\circ$ to $170^\circ$ (figure 11, zone A). In the $C_{\text{Coup}}$ range from 50 to 200 nF (zone B on figure 11), there was not stable relative phase (figure 9). When $C_{\text{Coup}}$ was greater than 200 nF (zone C on figure 11) oscillators synchronized in antiphase (figure 10) and period of oscillation was determined generally by $C_{\text{Coup}}$. This mode can be explained by larger $C_{\text{Coup}}$ recharging current, that hold switch of one oscillator in ON-state while voltage on another oscillator increase. Similar oscillation mode observed in work [5].

During numerical simulation (SPICE simulation) it was revealed that oscillation dynamic in this mode was caused by the non-linear resistance of VO$_2$ switches in the metallic state.

Changing of the relative phase for two oscillators was implemented by the method, proposed in work [5]. The circuit similar as for capacitive coupling (figure 5b) but without $R_{\text{OX}}$ was used. Serial resistor $R_{\text{S(1)}}$ value was changing in all range, where oscillation observed (from 42 to 64 kΩ), $R_{\text{S(2)}}$ value was fixed at 53 kΩ. The circuit and switches parameters were chosen equals: $V_{\text{DD}} = 80$ V, $R_{\text{i}} = 10$ Ω, $C = 100$ nF, $V_{\text{b}} = 0,99$ V, $V_{\text{h}} = 0,44$ V, $R_{\text{off}} = 1,17$ kΩ. Simulation with large $C_{\text{Coup}} = 1$ μF was carried out. Synchronization observed in all range of $R_{\text{S(1)}}$ and relative phase variation range $\Delta \phi$ was about $70^\circ$ (figure 12). The simulation with small $C_{\text{Coup}}$ from 1 to 7 nF showed that synchronization occurs in the certain range of $R_{\text{S(1)}}$ (figure 13), which increase with increasing $C_{\text{Coup}}$ value. Relative phase changes linearly on the most of the synchronization range. On the other hand, increasing $C_{\text{Coup}}$ value leads to decreasing relative phase variation range $\Delta \phi$. The maximum of relative phase variation range $\Delta \phi$ appear at $C_{\text{Coup}} = 1$ nF and its value is more than $310^\circ$.

5. Conclusion

Thus, capacitive coupling is more suitable for synchronization of oscillators based on VO$_2$ switches, because it provides stable synchronization and galvanic isolation between oscillators. This type of coupling can be used in systems that consist of a larger number of oscillators fully coupled to each other or coupled in a star configuration.

The simulation of the relative phase changing for two capacitively coupled oscillators by tune serial resistor $R_{\text{S}}$ shows that small $C_{\text{Coup}}$ provides the larger range of available relative phase. The large $C_{\text{Coup}}$ can be useful when synchronization of oscillators in all range of serial resistor value needed.

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