RF Single-Pole Double-Throw Switch Based on Two-Port Memistor

J Vavra¹, J Bajer² and D Biolek¹,³

¹ Department of Electrical Engineering, University of Defence, Kounicova 65, Brno, Czech Republic
² Department of Aviation Technology, University of Defence, Kounicova 65, Brno, Czech Republic
³ Department of Microelectronics, Brno University of Technology, Technicka 10, Brno, Czech Republic

jiri.vavra@unob.cz

Abstract. The paper introduces a novel memristive two-port element for an efficient construction of Radio Frequency (RF) single-pole double-throw (SPDT) switches, the so-called Two-Port Memistor (TPM). In comparison with the classical Widrow memistor whose resistance depends on the charge passing through the auxiliary terminal, the resistance of the TPM is governed by the controlling signal applied to the programming gate. It is demonstrated that the SPDT switch can be constructed via two TPMs such that the RF chokes providing DC references and capacitors for AC couplings are no longer necessary. Since the TPM-based switches provide elegant and much simpler circuit solutions than the currently developed memristive switches, this paper could stimulate the research towards manufacturing the TPM as a solid-state device.

1. Introduction

The architecture of modern RF and microwave systems is rapidly changing. In addition to the conventional blocks such as the amplifiers, filters, mixers, impedance matching circuitry, limiters, phase shifters and others, the RF switches and other devices supporting flexible re-configuration of the signal processing chain play an important role. Typical examples are systems utilizing multiple antennas, Multiple-Input Multiple-Output (MIMO) systems, systems with diversity reception, etc. These devices need to be equipped with internal components that provide their mutual interconnection. Such components are typically based on solid-state RF switches. Another application where RF switches have become particularly important are T/R (Transmit/Receive) modules of radars and other devices utilizing AESA (Active Electronically Scanned Array) antennas, where the RF switch serves to select between the transmission and the reception signal path. These switches are usually based on Si PIN diodes, GaAs PIN diodes, GaAs MESFETs and HEMPTs, Si MOSFETs, SiGe HBTs, or GaN HEMPTs [1].

Recently, the RF switches employing the memristive devices arrived on the scene [2]-[5]. Memristors [6] or more general memristive systems [7] are two-terminal elements whose memristance depends on the internal state, which reflects the history of terminal voltage and current. The RF switch utilizing the memristive technology, called RFMS (RF Memristor Switch), profits from the memristor
nonvolatility and nano-scale. The low insertion loss, high isolation, and high cut-off frequency make the RFMS a perspective element for controlling future-generation RF applications. A typical topology of the single-pole double-throw RFMS is shown in Fig. 1. The inductors \( L_{DC} \) provide DC grounding of the corresponding memristors \( M_1 \) and \( M_2 \), and the \( L_B \) arranges the DC path for driving both memristors via the controlling voltage \( V_{ctrl} \) which programs the \( M_1 \) and \( M_2 \) memristances to \( R_{on} \) and \( R_{off} \) for \( V_{ctrl} > 0 \) and to \( R_{off} \) and \( R_{on} \) for \( V_{ctrl} < 0 \). The capacitors provide the AC coupling.

**Figure 1.** Conventional SPDT RF switch with two memristors [5].

The goal is to replace the memristors in Fig. 1 with another type of device that will also provide the nonvolatile switching while concurrently enabling the removal of complicated DC/AC circuitries. The two-port memistors can be promising candidates for such nonvolatile switches. This paper is an extended version of already published conference paper [8].

### 2. Two-Port Memistor

In accordance with the original definition of the memistor [9], [10], it behaves as a linear resistor whose resistance is controlled by the charge flowing to the auxiliary third high-impedance terminal. Since the ideal RF switch should also behave as a linear resistor programmed to \( R_{on} \) and \( R_{off} \) states, the memistor seems to be a better candidate for this role than the memristor whose resistance is modulated by the over-threshold signal. However, the current flowing to the controlling gate of the memistor requires a closed DC loop similar to classical memristor switching. The newly suggested two-port memistor with its schematic symbol as in Fig. 2 overcomes this problem by introducing one additional programming gate whose driving signal does not penetrate to the signal path. The voltage-current and state equations are

\[
\begin{align*}
    v &= R(x) i, \\
    F(x, \dot{x}, v_{ctrl}) &= 0
\end{align*}
\]

where \( R \) is the memistor resistance, \( x \) is the internal state of the memistor, and \( F \) is a nonlinear function describing the dynamics of the process of programming the resistance.

It is important for the state variable governing the resistance to be programmed via a signal that is isolated from the resistive port. For the RF switch described in [2], the switch-on resistance is given by a conducting filament formed within the 35-nm air gap between two electrodes after applying a voltage ramp (0 to 3 V) across these electrodes. The state variable \( x \) in (1) reflects the geometry of this filament. Now it is necessary to apply a different mechanism for initiating the filament via another pair of electrodes. In any case, the corresponding model (1) of the related processes should be accordingly accommodated. For example, one may expect that the memistor state will be also modulated by the voltage or current of the resistive gate and that the resistance will also depend on these quantities. The latter means that the on-state switch would behave as an extended memristor. This observation is in accordance with the conclusions in [2].

In order to reflect the tunneling nature of the conductivity of MIM structures, the VTEAM model is used in [5] as a useful approximation of the more complex Pickett model [11]. For a more accurate
modeling of the on-state memistor, which can subsequently be used for small-signal transient and AC analyses, we used an approximation of the current-voltage Simmons equations from [12]:

\[
i = \text{sgn}(v)k_1k_2\left[\sinh((k_3 + k_4)x)|v| + k_5(e^{k_6|x|} - 1)\right]
\]  

(2)

where \(k_1\) to \(k_6\) are the fitting parameters and \(x\) is the width of the tunnel barrier, the latter playing a similar role as the width of the conducting filament from [2].

3. Memistor-based SPDT switch

Two TPMs can be interconnected as shown in Fig. 3 such that the resulting SPDT switch does not require any additional AC/DC circuitries. The programming ports are in anti-parallel configuration, but they can be easily reconfigured according to the prospective demands for an independent programming.

![Figure 3. Circuit diagram of proposed memistor-based SPDT switch.](image)

The SPICE simulation of the SPDT switch from Fig. 3 was performed with the TPM model derived from the RF lumped model of the nanoscale memristive switch published in [5]. Note that this model describes the small-signal behavior of the switch specimen from [2]. The corresponding equivalent circuit in Fig. 4 models only the resistive, not the programming port of the two-port memistor.

![Figure 4. Equivalent model of the resistive part of two-port memistor [5].](image)

![Figure 5. Simulated insertion loss and isolation of the TPM-based SPDT switch.](image)
For the simulation, all the parameters in Fig. 4 except for the $R$ (memistor resistance) were obtained from [5]. The resistive part of the memistor was modeled via the nonlinear equation (2), whose parameters fitted the dynamics of the TiO$_2$ memristor [12], with the $R_{on}$ and $R_{off}$ values specified in [2]. Fig. 5 shows the frequency characteristics of insertion loss and isolation of the switch which are in accordance with results in [5]. The blue line represents the insertion loss induced by an ON-state TPM$_1$ connected between the $P_1$ and $P_2$ terminals. The red one gives the isolation between the $P_1$ and $P_3$ terminals, when the OFF-state TPM$_2$ is connected to $P_3$. The insertion loss and isolation at 30 GHz are approx. 0.25 dB and 40 dB, respectively.

4. Conclusion
A new circuit idea of nonvolatile RF switching is proposed. The two-terminal memistor is used for constructing the single-pole double-throw RF switch, which combines the advantages of the recently published memristor-based and the traditional FET RF switches. The main benefits of the proposed solution are simple circuitry, reduced power consumption due to the non-volatility of memristive devices, and simple switch programming via auxiliary ports located beyond the RF signal path.
To model the above memistor, the approximation was used of the current-voltage Simmons equations, which reflect the tunneling nature of the conductivity of MIM structures. The SPICE simulations are in accordance with the hitherto published results.

5. References
[1] Bahl I J 2014 Control Components Using Si, GaAs, and GaN Technologies (Boston: Artech House) p 310
[2] Pi S, Ghadiri-Sadrabadi M, Bardin J C and Xia Q 2015 Nanoscale Memristive Radiofrequency Switches Nature Communications 6 pp 1–9
[3] Nessel J A, Lee R Q, Mueller C H, Kozicki M N, Ren M and Morse J 2008 A Novel Nanoionics-based Switch for Microwave Applications Proc. Int. Microwave Symp. Dig. (Atlanta) pp 1050–54
[4] Vena A, Perret E, Tedjini S, Vallée C, Gonon P and Mannequin C 2012 A Fully Passive RF Switch based on Nanometric Conductive Bridge Proc. Int. Microwave Symp. Dig. (Montreal) pp 1–3
[5] Wainstein N and Kvatinsky S 2018 A Lumped RF Model for Nanoscale Memristive Devices and Nonvolatile Single-Pole Double-Throw Switches IEEE Trans. on Nanotechnology 17 pp 873–83
[6] Chua L O 1971 Memristor—The Missing Circuit Element IEEE Trans. Circuit Theory CT-18 pp 507–19
[7] Chua L O and Sung Mo Kang 1976 Memristive devices and systems Proceedings of the IEEE 64 pp 209–23
[8] Vavra J, Bajer J and Biolek D 2018 RF Single-Pole Double-Throw Switch Based on Memistor 2018 IEEE Radio and Antenna Days of the Indian Ocean (RADIO) (Grand Port) pp 1-2
[9] Widrow B 1960 An adaptive “ADALINE” neuron using chemical memistors Stanford Electronics Laboratories Technical Report No. 1553-2 p 23
[10] Adhikari S P and Kim H 2012 Why are memristor and memistor different devices? IEEE Trans. Circ. Syst. 59 pp 2611–8
[11] Pickett M D, Strukov D B, Borghetti J L, Yang J J, Snider G S, Stewart D R and Williams R S 2009 Switching dynamics in titanium dioxide memristive devices Journal of Applied Physics 106 p 074508
[12] Biolek D, Kolka Z, Biolkova V, Biolek Z, Potrebic M and Tosic D 2018 Modeling and simulation of large memristive networks Int. J. Circ. Theor. Appl. 46 pp 50-65

Acknowledgments
This work was supported by the Project of Specific Research at K217, Research of sensor and control systems to achieve battlefield information superiority, UD Brno, and also by the Czech Science Foundation under grant no. 18-21608S.