Application of Memristors in Microwave Passive Circuits

Milka POTREBIC, Dejan TOSIC

University of Belgrade – School of Electrical Engineering, Bulevar kralja Aleksandra 73, 11000 Belgrade, Serbia

milka_potrebic@etf.rs, tosic@etf.rs

Abstract. *The recent implementation of the fourth fundamental electric circuit element, the memristor, opened new vistas in many fields of engineering applications. In this paper, we explore several RF/microwave passive circuits that might benefit from the memristor salient characteristics. We consider a power divider, coupled resonator bandpass filters, and a low-reflection quasi-Gaussian lowpass filter with lossy elements. We utilize memristors as configurable linear resistors and we propose memristor-based bandpass filters that feature suppression of parasitic frequency pass bands and widening of the desired rejection band. The simulations are performed in the time domain, using LTspice, and the RF/microwave circuits under consideration are modeled by ideal elements available in LTspice.*

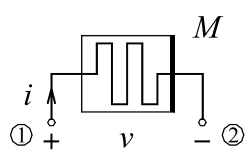
Keywords

Memristor, microwave passive circuit, filter.

1. Introduction

The memristor is a two-terminal one-port electric circuit element, envisioned and postulated by Chua [1]-[3], characterized by a constitutive relation between the time integral of the element's current and the time integral of the element's voltage. Memristor symbol and the constitutive relation are shown in Fig. 1.

$$F(q(t),\varphi(t))=0 \qquad q(t)=\int_{-\infty}^{t} i(\tau)\,\mathrm{d}\tau$$



$$\varphi(t)=\int_{-\infty}^{t} v(\tau)\,\mathrm{d}\tau$$

Fig. 1. Memristor symbol and constitutive relation.

Conventionally, q is called the charge and φ is called the flux of the memristor but these quantities need not have any physical interpretations.

The memristor is said to be charge-controlled if its constitutive relation can be expressed by

$$\varphi=\Phi(q) \tag{1}$$

where $\Phi(q)$ is a continuous and piecewise-differentiable function with bounded slopes. Differentiating (1) with respect to time t, the memristor port equation is obtained

$$v=\frac{\mathrm{d}\varphi}{\mathrm{d}t}=\frac{\mathrm{d}\Phi(q)}{\mathrm{d}q}\frac{\mathrm{d}q}{\mathrm{d}t}=M(q)\,i \tag{2}$$

where

$$M(q)=\frac{\mathrm{d}\Phi(q)}{\mathrm{d}q} \tag{3}$$

is called the memristance at q. Just as memristor is an acronym for memory resistor, memristance is an acronym for memory resistance. It should be noted that the memristance at any time depends on the entire past history of the element's current. Equations (2) and (3) define an ideal memristor.

The memristor exhibits a distinctive "fingerprint" characterized by a pinched hysteresis loop, a double-valued Lissajous figure passing through the origin, confined to the first and the third quadrants of the v-i plane. Consequently, Chua [2] establishes the following identification of memristors: "Any two-terminal device which exhibits a pinched hysteresis loop in the v-i plane when driven by any bipolar periodic voltage or current waveform, for any initial conditions, is a memristor. The loop shrinks to a straight line whose slope depends on the excitation waveform, as the excitation frequency tends to infinity."

An important and salient feature of the memristor is that it exhibits non-volatile memory [3]: when a memristor is opened or short-circuited, or when the excitation is switched off, the memristor holds its charge and the flux and "memorizes" its memristance – it is a resistor with memory.

In addition to the three traditional fundamental passive circuit elements, the resistor, the capacitor and the inductor, the memristor is the fourth basic ideal (pure) element of electric circuits characterized by a state-dependent Ohm's law. In a broader sense, the memristor begins a subclass of memristive systems introduced by Chua and Kang [4].

Extensive analysis of the memristor salient properties and the detailed memristor fingerprints summary, from the simulation and modeling viewpoint, are presented in [5] along with the generalization to memristive systems and non-electrical applications.

DOI: 10.13164/re.2015.0408

The successful implementation of memristor is a titanium-dioxide nano device fabricated at Hewlett-Packard Laboratories [6]. This pure solid-state implementation of memristor, without an internal power supply, is sometimes referred to as the HP memristor.

The direct physical realization of memristor as the fourth basic circuit element opens new vistas and research interests in many application fields ranging from digital memories to analog devices. Moreover, special issues of the eminent IEEE publications have been dedicated to this emerging technology [7], [8].

Despite an immense interest among researchers and engineers on the memristor, commercially available memristors are still not available, so reliable circuit models are needed to explore and simulate application circuits which exploit memristor's potentials. SPICE (Simulation Program with Integrated Circuit Emphasis) is a general-purpose simulation program which allows the testing of complex circuits before they are actually implemented experimentally, so it can be useful for simulating memristors and memristor-based circuits [9]-[24].

Memristors hold promise for use in diverse applications ranging form digital memories and logic to analog circuits and systems. In analog circuits, the resistance may require a continuous value, so memristors might be used as configurable components and the desired resistance could be initialized by a specific procedure, different from the expected circuit operation [25]-[28].

Application of memristors in RF/microwave circuits, and in a broader context in electromagnetic systems, is another challenging field for researchers and engineers. Bray and Werner [29] utilize memristors as electromagnetic switches to implement a frequency selective surface. Werner and Gregory [30] analyze a memristor-based electromagnetic absorber. Sombrin et al. [31] use the ideal memristor as a behavioral model for passive non-linearity in filters, antennas and connections. Gregory and Werner [32] analyze a polarization-switchable patch antenna with memristors as microwave switches. Xu et al. [33] analyze a planar ultra-wideband (UWB) monopole antenna with memristor-based reconfigurable notched band. Wu at al. [34] explore the feasibility of fabrication transient photonic memristor at microwave frequencies with metamaterials. Xu et al. [28] incorporate a memristor in a microstrip transmission line as a load, analyze single memristor-loaded split-ring resonator filter, and utilize a memristor as a carrier-wave modulator connecting a microstrip patch antenna to the ground.

In this paper we focus on the application of memristors in microwave passive circuits, such as power dividers, lossy lowpass filters and coupled-resonator bandpass filters.

2. LTspice Model of the Ideal Memristor

LTspice [35] is used in this work to explore various microwave circuits with memristors by the time-domain simulations, i.e. the SPICE nonlinear transient analysis.

The microwave circuits will be represented by ideal circuit elements available in LTspice, such as resistors, capacitors, lossless transmission lines, independent voltage sources, and behavioral voltage and current sources. As pointed out in [5, p. 158] "Even though these elements cannot be manufactured in their ideal representations, they are indispensable as modeling tools for describing and understanding the essence of processes within existing systems."

The LTspice model of the ideal memristor, Fig. 2, is based on the memristorR1 model and subcircuit proposed by Biolek et al. [24, Fig. 1, p. 950], [5, Ch. 4, p. 141–142]. The corresponding fingerprint, a pinched hysteresis loop passing through the origin, is shown in Fig. 3.

Initial microwave circuit design often starts with idealized microwave components. Therefore, a memristor-based microwave circuit composed of ideal elements is expected to give a good insight into the circuit operation and performance. This work considers only circuits with ideal elements and is meant to be a proof-of-concept on the potential application of memristors for RF/microwave cir-

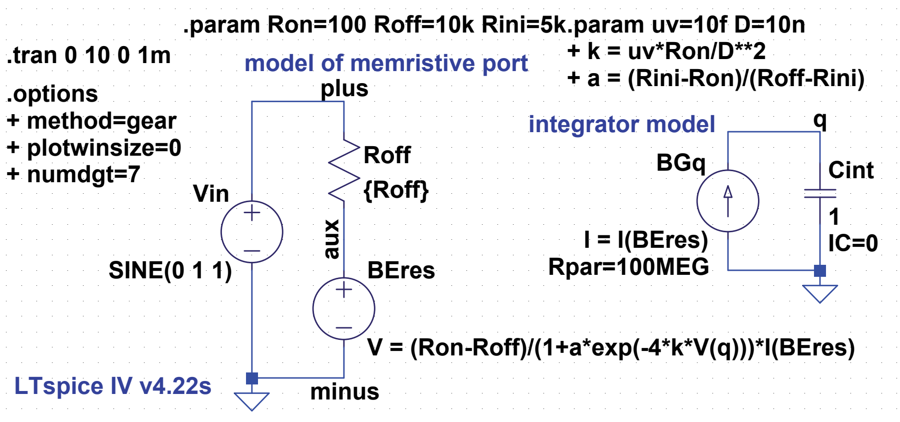


Fig. 2. LTspice model of the ideal memristor based on the memristorR1 model and subcircuit proposed by Biolek et al. [24], [5].

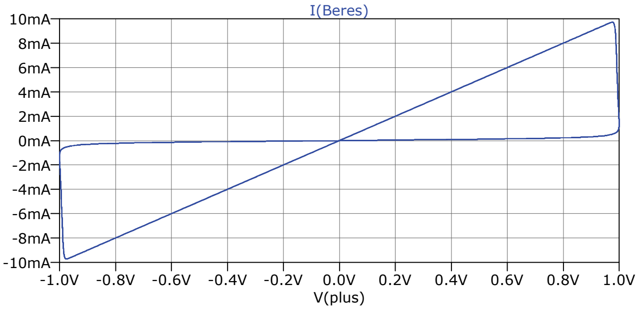


Fig. 3. Fingerprint of the ideal memristor of Fig. 2: Pinched hysteresis loop, a double-valued Lissajous figure passing through the origin, confined to the first and the third quadrants of the v-i plane.

cuits. Our model of the memristor is a simplified version of a really operating threshold-type memristive device.

We use the ideal memristor as a linear resistor with a programmable resistance, which can be adjusted with accuracy and reproducibility by auxiliary programming circuitry. It is assumed that the signal to be processed, e.g. filtered, should under no circumstance affect the value of the (programmed) memristance. The resistance value is equal to Rini, shown in Fig. 2, in our modeling.

It is expected that at frequencies higher that 100 MHz, which are typical for RF/microwave circuit operation, the memristor has behavior similar to that of a linear resistor. Consequently, it can be assumed that the distortions of the signals processed by memristor-based microwave circuits should be negligible. We increase the excitation frequency of Fig. 2 to analyze the memristor dynamics with regard to the required frequency behavior. For frequencies over 100 kHz the pinched hysteresis loop of Fig. 3 degenerates to straight line implying a limiting frequency for a linear operation and the FFT analysis shows that the higher harmonics are more that 80 dB below the fundamental.

Precision variable resistors are important for RF/microwave circuits, e.g. in impedance matching and for tuning the frequency characteristics. Therefore, memristors might be promising elements for this application field.

3. The Wilkinson Power Divider

The Wilkinson power divider [36] is a passive three-port linear time-invariant microwave network, matched at all ports, which is used for power division or power combining. In power division, an input signal is divided into two output signals of lesser power. The divider is usually implemented in planar technologies, such as microstrip and stripline. It can be designed with an arbitrary power division ratio, but we shall consider the equal-split (3 dB) case, only.

The ideal Wilkinson power divider 3 dB, Fig. 4, consists of a resistor and two quarter-wave lossless transmission-line sections. We replace the resistor with a memristor, excite the divider with a 2 V amplitude 1 GHz sinusoidal signal, and observe the response at the two output ports terminated by matched loads. The reference (nominal) impedances of all ports are 50 Ω. The scattering parameters of the divider, at the operating frequency, are given by

$$\mathbf{S} = \frac{-j}{\sqrt{2}}\begin{vmatrix} 0 & 1 & 1 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{vmatrix}, \; j = \sqrt{-1}\,. \tag{4}$$

The instantaneous power at the divider output ports is shown in Fig. 5. The average input power is 10 mW and the average output power is 5 mW per port that verifies the equal-split power division.

The Fast Fourier Transform (FFT), that is a built-in option of the LTspice waveform viewer, is used to estimate the frequency content of the output signal, Fig. 6, in order to verify that the memristor acts as a linear resistor and does not introduce spectral impurities. Obviously, the amplitude spectrum of Fig. 6 confirms that the output signal is sinusoidal at 1 GHz, which is the input signal frequency.

We hope that memristors might be useful in the design of Wilkinson power divider because the memristance can be adjusted – programmed – precisely to a desired value which is not the case with ordinary microwave resistors.

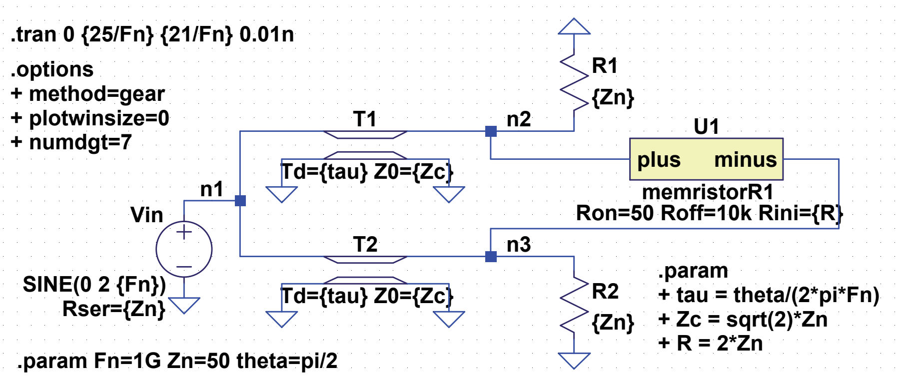


Fig. 4. LTspice model of the ideal Wilkinson power divider 3 dB.

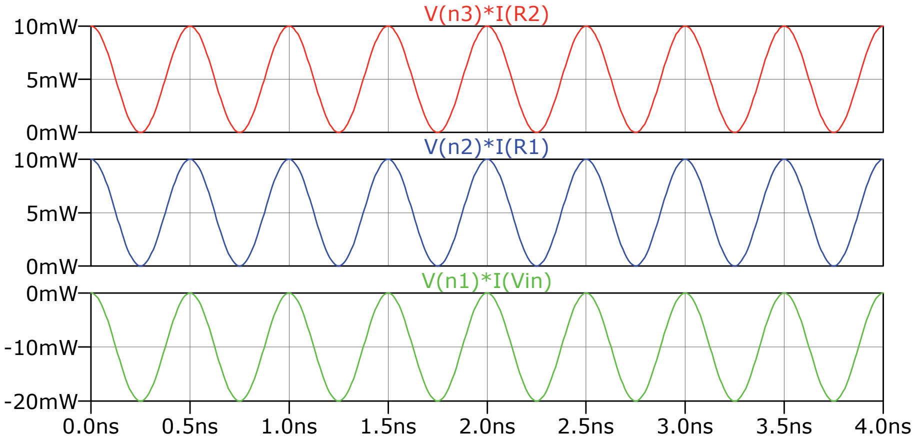


Fig. 5. Instantaneous power of the ideal Wilkinson power divider 3 dB shown in Fig. 4.

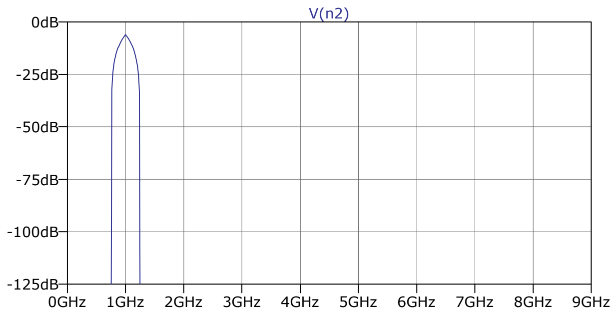


Fig. 6. Amplitude spectrum of the output signal of the Wilkinson power divider shown in Fig. 4.

4. The Hairpin-line Bandpass Filter

The hairpin-line bandpass filter [37] is a coupled-resonator filter realized with a cascade of pairs of parallel-coupled open-circuited transmission lines. It is suitable for planar implementations, such as microstrip technology, as it is easy to fabricate due to the absence of short circuits. Practically, this filter is obtained by folding the planar half-wavelength resonators into a "U" shape. For an accurate design of the hairpin-line bandpass filter full-wave electromagnetic simulations are required.

Coupled transmission lines are not available in LTspice, so a subcircuit should be created to represent a section of the open-circuited pair of coupled transmission lines. We assume ideal coupled lines, so the equivalent networks elaborated in [38, Fig. 3.28, p. 100–101] can be used to construct the network shown in Fig. 7, i.e. the LTspice subcircuit for modeling the hairpin-line filter.

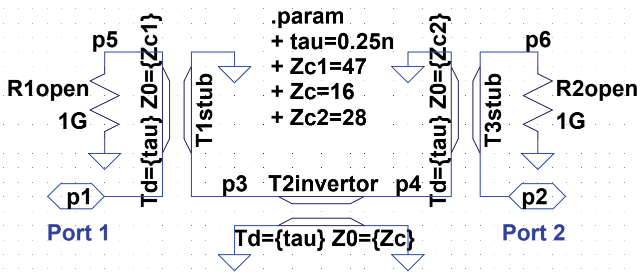


Fig. 7. Equivalent network for the section of a pair of ideal coupled transmission lines open-circuited at two ports.

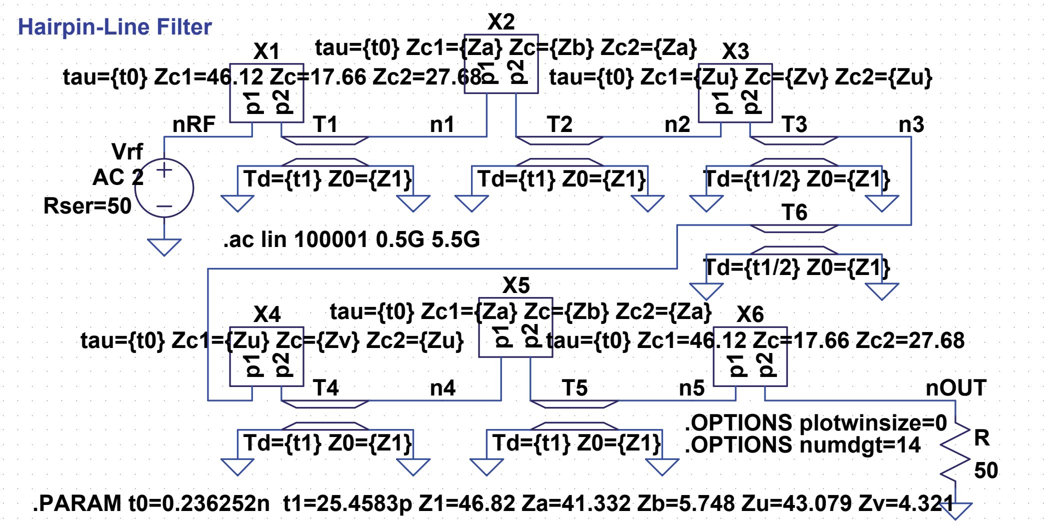


Fig. 8. LTspice model of the hairpin-line bandpass filter. The networks marked by X are subcircuits shown in Fig. 7. The filter is symmetrical with respect to node n3. The voltage source amplitude is set to 2 V in order to generate the transmission scattering parameter.

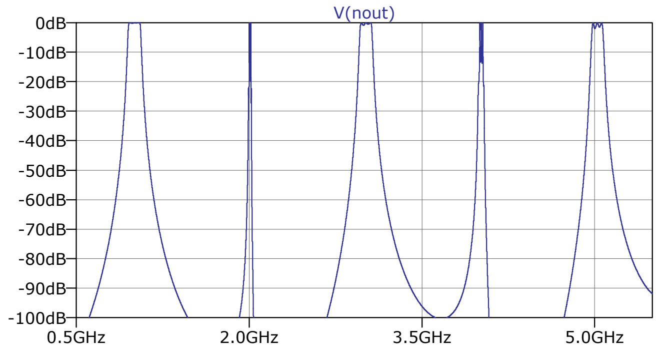


Fig. 9. Magnitude of the transmission scattering parameter of the hairpin-line filter. The frequency response has undesired pass bands.

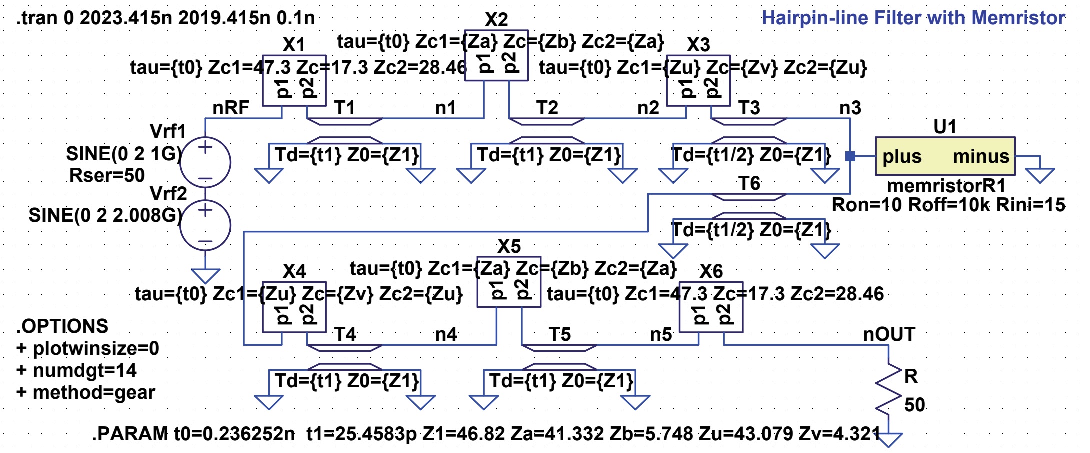


Fig. 10. LTspice model of the ideal hairpin-line bandpass filter with memristor, which suppresses some undesirable pass bands and widens the rejection band. The filter is excited by two sinusoidal RF signal. The frequency of the first signal is at 1 GHz, which is the center frequency of the pass band, so the signal passes through the filter. The second signal at 2.008 GHz, which is the frequency inside the first undesired pass band of the filter from Fig. 8, is suppressed by insertion of the memristor.

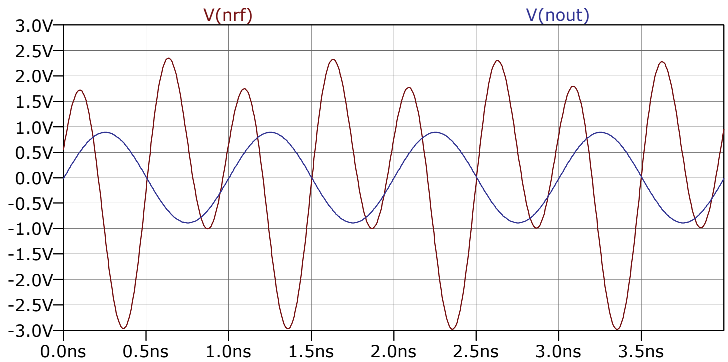


Fig. 11. Time-domain response of the hairpin-line filter with memristor. The output signal V(nout) is sinusoidal at 1 GHz.

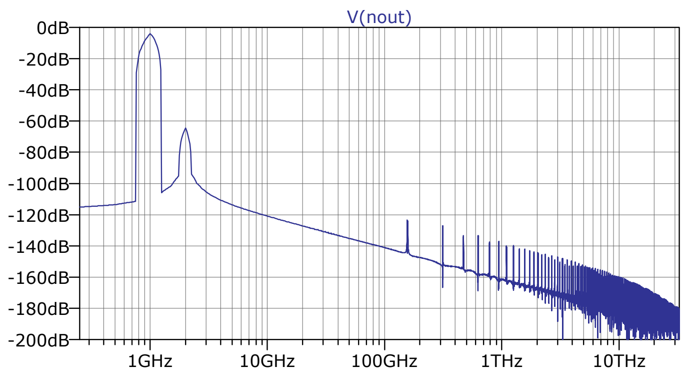


Fig. 12. Amplitude spectrum of the output signal of the hairpin-line filter with memristor. The input signal component at 2.008 GHz is suppressed by about 60 dB.

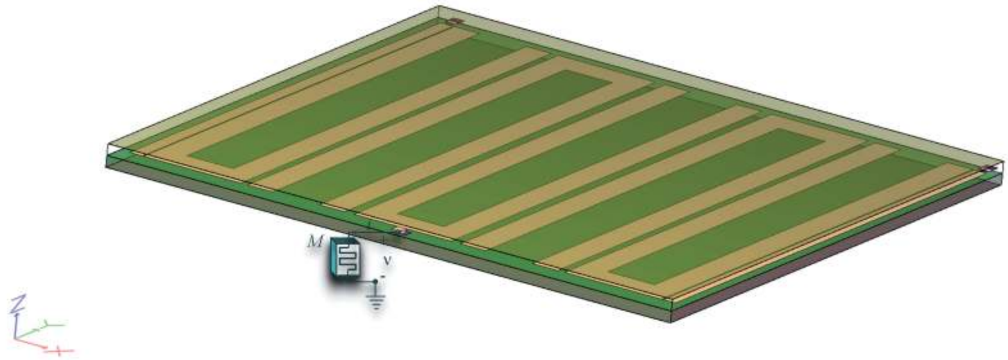


Fig. 13. 3D model of the hairpin-line filter with memristor.

The LTspice model of the filter is shown in Fig. 8 and the magnitude of the transmission scattering parameter is presented in Fig. 9. The filter is designed as a bandpass filter with the center frequency at 1 GHz and only one pass band is desired. Evidently, undesired pass bands exist, which is a known side effect of all-transmission-line filter realizations.

The hairpin-line filter of Fig. 8 is an electrically symmetrical network with respect to node 3. Symmetrical passive two-port networks can be conveniently analyzed by using Bartlett's bisection theorem [39], Bartlett and Brune's theorem [39], and the even- and odd-mode analysis [37].

We propose, in this work, insertion of a grounded memristor connected to node 3, as shown in Fig. 10, in order to suppress some undesired pass bands and to widen the rejection band of the filter. It can be shown that this approach suppresses parasitic pass bands at frequencies which are even multiples of the desired pass-band center frequency.

The time-domain response of the ideal memristor-based hairpin-line bandpass filter is shown in Fig. 11. The Fast Fourier Transform of the response is presented in Fig. 12. The physical 3D model of the filter is shown in Fig. 13.

5. Capacitively Coupled Resonator Bandpass Filter

The capacitively coupled resonator filter is useful for narrowband applications, usually with bandwidths of less than 10% of center frequency [37]. It can be implemented in planar technologies, e.g. as the end-coupled microstrip half-wavelength resonator bandpass filter. The resonators are open-end microstrip resonators that are approximately a half guided wavelength long at the center frequency of the bandpass filter. The resonators are capacitively coupled through the gap between the two adjacent open ends.

The LTspice model of the ideal capacitively coupled resonator filter is shown in Fig. 14 and the magnitude of the transmission scattering parameter is presented in Fig. 15. The filter is designed as a narrowband band-pass filter with the center frequency at 6 GHz, only one pass band is desired, but undesired pass bands exist.

We propose insertion of a grounded memristor connected to the middle of the central resonator, as shown in Fig. 16, in order to suppress some undesired pass bands (at even multiples of the desired pass-band center frequency) and to widen the rejection band of the filter. The corresponding time-domain response is shown in Fig. 17. The Fast Fourier Transform of the response is presented in Fig. 18.

The role of the grounded memristor connected to the middle of the central resonator in Fig. 16 can be explained as follows. The ideal transmission lines, T1, T2 and T3 are resonators that are approximately a half guided wavelength long at the center frequency of the bandpass filter, which is 6 GHz. The line T3 is split in two equal-length parts T3a and T3b, which are the quarter-wavelength lines at 6 GHz. A quarter-wavelength of transmission line is the simplest realization of the ideal impedance inverter [37, p. 56]. A shunt resistor with an inverter on each side is equivalent to a series resistor. It introduces some loss, about 0.4 dB, but it does not change the shape of the desired pass band. However, in the frequency band around 12 GHz, T3a and T3b are $\lambda/8$-lines and the shunt resistor with the $\lambda/8$-line on each side is equivalent to a two-port attenuating network.

It should be noted that the filter of Fig. 16 is an electrically symmetrical network with respect to node n0 and can be conveniently analyzed by using Bartlett's bisection theorem [39].

6. Low-reflection Transmission-line Quasi-Gaussian Lowpass Filter with Lossy Elements

Gaussian-like frequency-domain transfer functions are often desirable in digital signal transmission because they do not yield overshoots and ringing in the time domain, so a special class of low-reflection filters is required. Lossy elements are introduced in the filter realization in order to achieve a good matching.

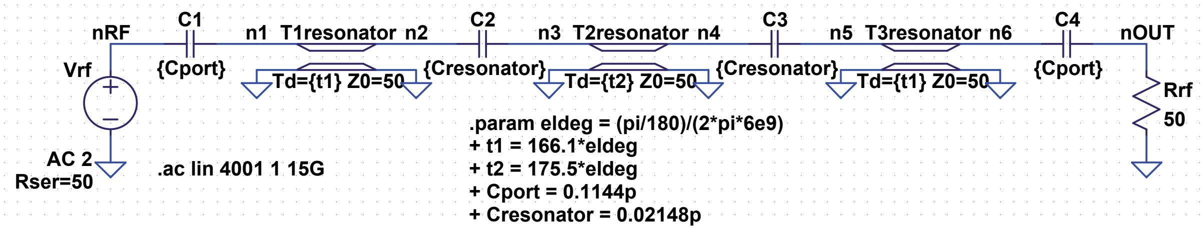


Fig. 14. LTspice model of the ideal capacitively coupled resonator bandpass filter. The filter is symmetrical about the central resonator designated by T2resonator. The voltage source amplitude is set to 2 V in order to generate the transmission scattering parameter.

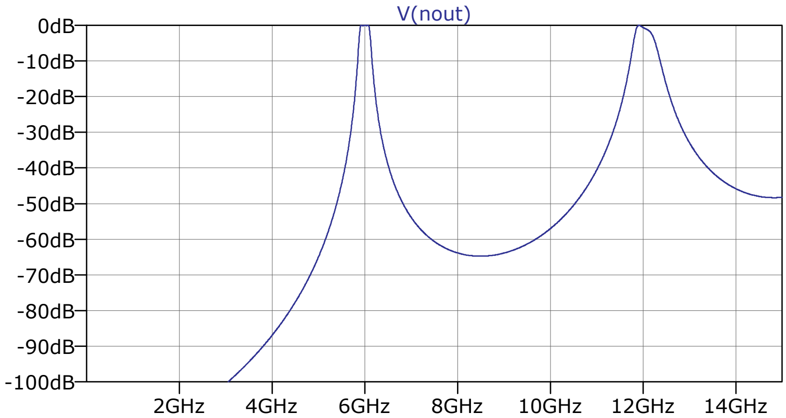


Fig. 15. Magnitude of the transmission scattering parameter of the ideal capacitively coupled resonator bandpass filter. The frequency response has undesired pass bands.

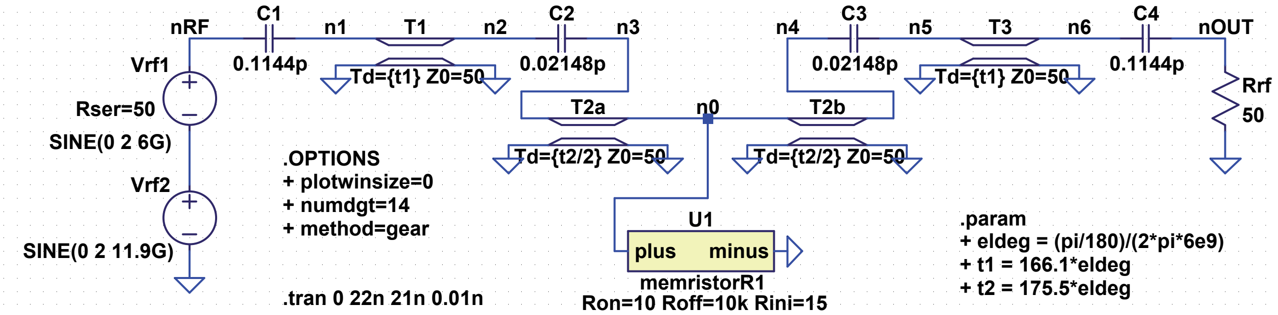


Fig. 16. LTspice model of the ideal capacitively coupled resonator bandpass filter with memristor, which suppresses some undesirable pass bands and widens the rejection band. The filter is excited by two sinusoidal RF signal. The frequency of the first signal is at 6 GHz, which is the center frequency of the pass band, so the signal passes through the filter. The second signal at 11.9 GHz, which is the frequency inside the first undesired pass band of the filter from Fig. 14, is suppressed by insertion of the memristor.

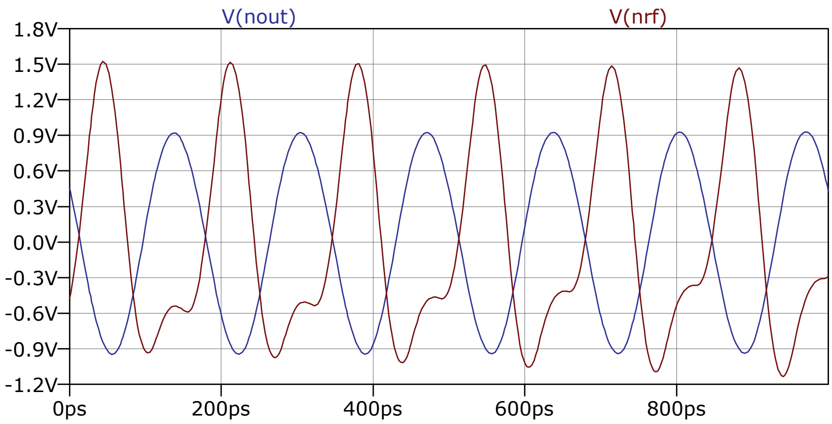


Fig. 17. Time-domain response of the capacitively coupled resonator filter with memristor. The output signal V(nout) is sinusoidal at 6 GHz.

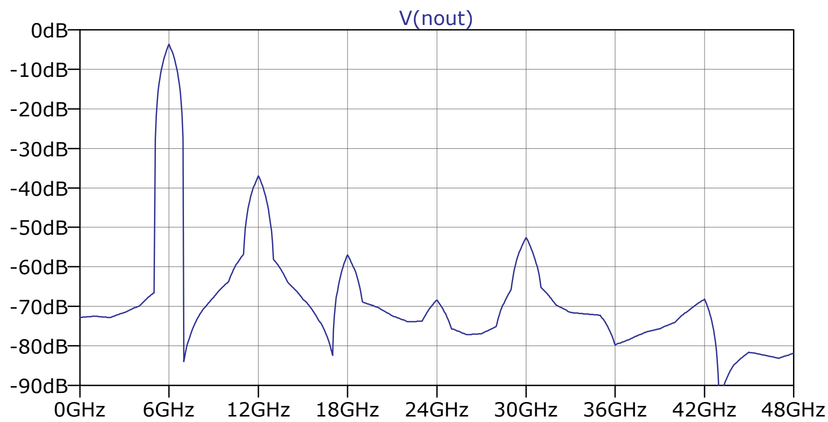


Fig. 18. Amplitude spectrum of the output signal of the capacitively coupled resonator filter with memristor. The input signal component at 11.9 GHz is suppressed by about 35 dB.

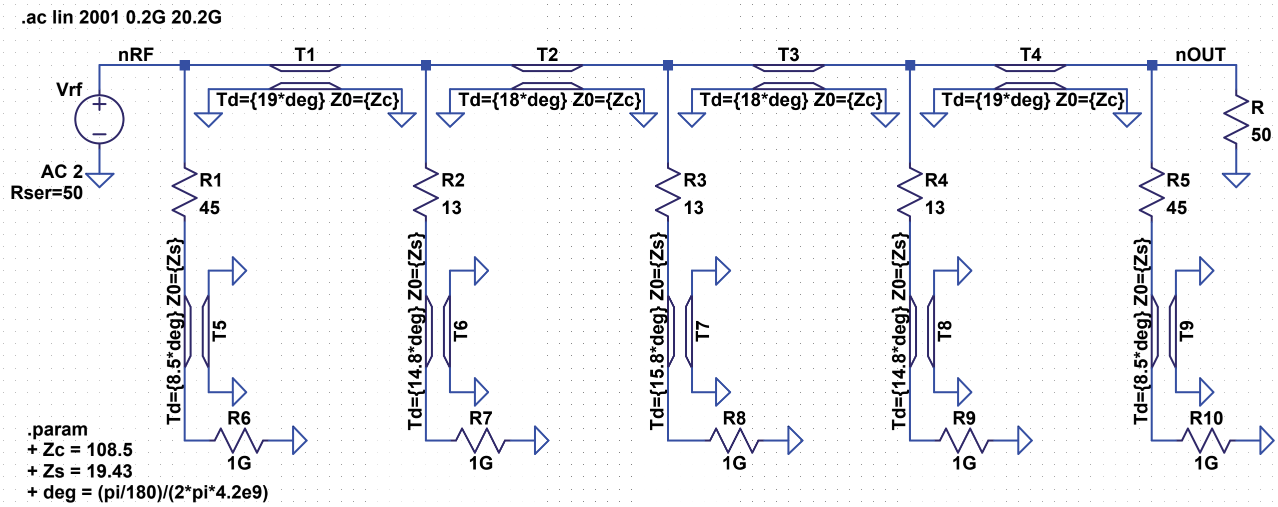


Fig. 19. LTspice model of the ideal low-reflection transmission-line quasi-Gaussian lowpass filter with resistors as lossy elements [40]. The voltage source amplitude is set to 2 V in order to generate the transmission scattering parameter.

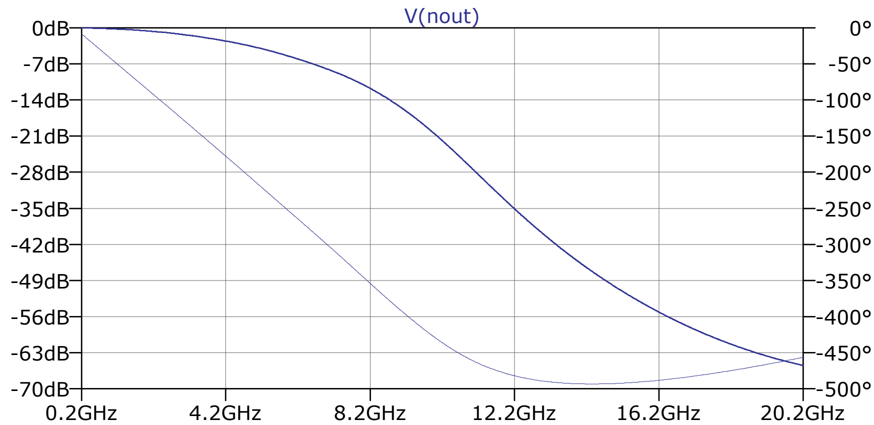


Fig. 20. Magnitude and phase of the transmission scattering parameter of the lossy lowpass filter. The phase characteristic (dotted) is very linear in a wide frequency range, thus implying the flat group delay characteristics. The amplitude characteristics is not very selective.

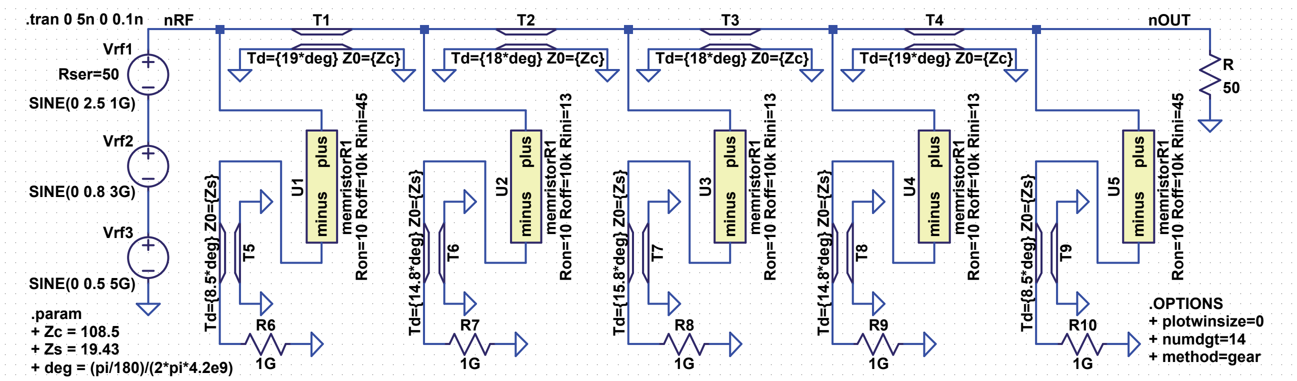


Fig. 21. LTspice model of the ideal low-reflection transmission-line quasi-Gaussian lowpass filter with memristor. The filter is excited by a sum of three sinusoidal signals of amplitudes 2.5 V, 0.8 V and 0.5 V, at frequencies 1 GHz, 3 GHz and 5 GHz, respectively. This excitation approximates a bipolar rectangular pulse train with the period of 1 ns and the amplitude of 2 V. The nominal impedances of the ports are 50 Ω, i.e. the source and load impedances are 50 Ω, so the signals at the input and output ports swing from –1 V to +1 V.

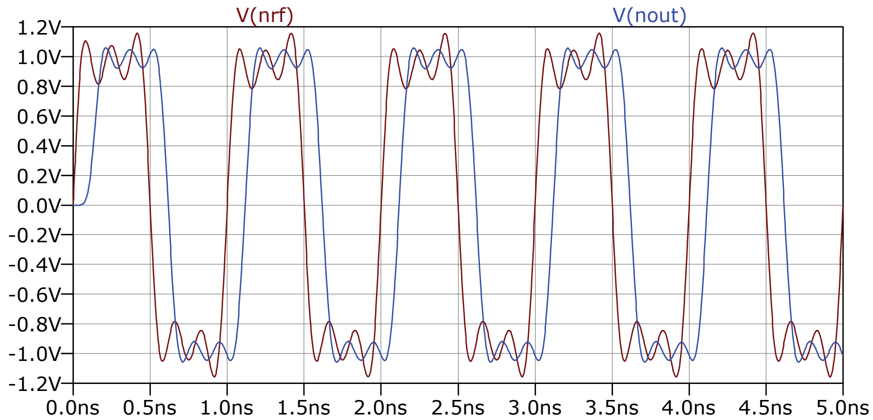


Fig. 22. Time-domain response of the lossy lowpass filter with memristor. The output signal V(nout) is a very good replica of the input signal V(nrf) due to the linear phase response, i.e. because of the nearly constant group delay.

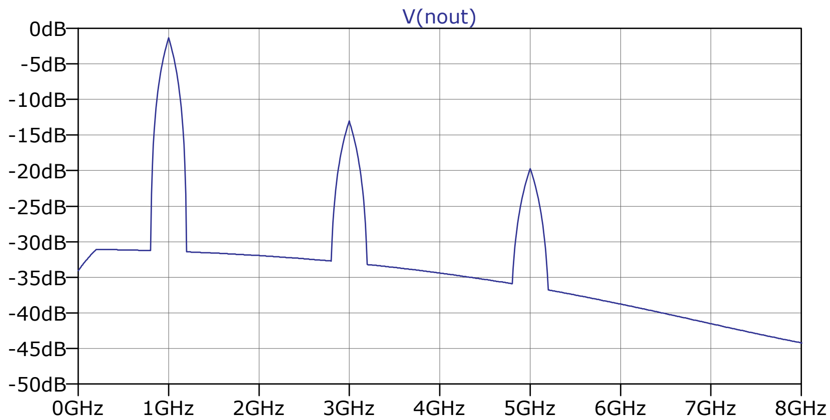


Fig. 23. Amplitude spectrum of the output signal of the lossy lowpass filter with memristor. The frequency content exactly corresponds to the input signal constructed of three sinusoidal signals that approximate a bipolar rectangular pulse train.

LTspice model of the lossy quasi-Gaussian lowpass filter proposed by Djordjević et al. [40] is shown in Fig. 19. The corresponding frequency response is shown in Fig. 20. The phase characteristic is linear in a wide frequency range.

We propose a modified lossy filter, Fig. 21, in which the resistors are replaced by memristors. The expected benefit of this approach is easier and precise tunability of the required resistances due to the inherent tunability feature of the memristor by programming its memristance. The corresponding response is shown in Fig. 22 and the frequency content of the output signal, generated by the LTspice FFT algorithm, is presented in Fig. 23.

7. Conclusion

Memory circuit elements are gaining significant attention owing to their ubiquity and potential use in miscellaneous areas of engineering. In this paper we have presented prospective utilization of memristors in microwave passive circuits. Memristors are exploited as linear resistors with programmable resistance, which can be accurately adjusted to a desired or specified value. Precise controllability of the memristance value might be important for tuning microwave circuits and optimizing their performance.

The signals processed by microwave circuits are typically sinusoidal with very high frequencies with respect to the memristor characteristics. Consequently, we expect that the memristor should keep its memristance at the initial value, which has been setup by some other control circuitry. Therefore, we may possibly replace resistors by memristors in the traditional designs of microwave circuits. It should be noted that the way of the memristor modeling in this case is not so much important because our model at such frequency range behaves as a pure linear resistor.

The Wilkinson power divider has been presented in this paper as an example of a microwave device that inherently comprises a resistor in its realization. The resistance value is critical for the expected operation, so the memristor might be a promising solution.

Coupled-resonator half-wavelength bandpass filters, the hairpin-line filter and the capacitively coupled filter, have been modified in this paper by inserting a memristor at the symmetry plane of the filters. The memristor-based filters have shown a wider rejection band and suppression of the unwanted pass bands at the frequencies that are even multiples of the center frequency of the desired pass band. By fine tuning the memristance value, a compromise between attenuation in the pass band and the amount of suppression could be achieved.

Lowpass transmission-line quasi-Gaussian filter has been presented in this paper as an example of a microwave filter that inherently comprises lossy resistive elements. The filter design requires optimization of the resistances to achieve the target performance – linear phase characteristic. Accordingly, the memristor might be beneficial as a replacement for resistors and the memristance electronic adjustment might be a solution to the problem.

Due to the unavailability of memristors, it has been necessary to use accurate models that would allow (1) experimenting with the memristor-based microwave circuits via simulation programs, LTspice in this work, and (2) studying the performance of the circuits.

Simulation of the considered memristor-based microwave circuits have verified the expected functionality and encouraged us to further explore the memristor deployment in the field of the RF/microwave engineering.

Acknowledgments

The authors would like to acknowledge the contribution of the EU COST Action IC1401. This work was supported in part by the Ministry of Education, Science and Technological Development of the Republic of Serbia under Grant TR 32005.

References

[1] CHUA, L. O. Memristor – The missing circuit element. *IEEE Transactions on Circuit Theory,* 1971, vol. CT-18, no. 5, p. 507 to 519. DOI: 10.1109/TCT.1971.1083337

[2] CHUA, L. O. Resistance switching memories are memristors. *Applied Physics A*, 2011, vol. 102, p. 765–783. DOI: 10.1007/s00339-011-6264-9

[3] CHUA, L. O. The fourth element. *Proceedings of the IEEE*, 2012, vol. 100, no. 6, p. 1920–1927. DOI: 10.1109/JPROC.2012.2190814

[4] CHUA, L. O., KANG, S. M. Memristive devices and systems. *Proceedings of the IEEE*, 1976, vol. 64, no. 2, p. 209–223. DOI: 10.1109/PROC.1976.10092

[5] TETZLAFF, R. (Editor) *Memristors and Memristive Systems*. New York: Springer, 2014. ISBN: 978-1-4614-9067-8 (Print) 978-1-4614-9068-5 (Online)

[6] STRUKOV, D. B., SNIDER, G. S., STEWART, D. R., WILLIAMS, R. S. The missing memristor found. *Nature*, 2008, vol. 453, no. 7191, p. 80 - 83. DOI: 10.1038/nature06932

[7] Memristors: Devices, Models & Applications. *Proceedings of the IEEE*, June 2012, vol. 100, no. 6, Special Issue. DOI: 10.1109/JPROC.2012.2197452

[8] Special Issue on Memristors: Theory and Applications. *IEEE Circuits and Systems Magazine*, April 2013, vol. 13, no. 2. DOI: 10.1109/MCAS.2013.2256252

[9] BIOLEK, Z., BIOLEK, D., BIOLKOVÁ, V. SPICE model of memristor with nonlinear dopant drift. *Radioengineering*, 2009, vol. 18, no. 2, p. 210–214.

[10] JOGLEKAR, Y. N., WOLF, S. J. The elusive memristor: Properties of basic electrical circuits. *European Journal of Physics*, 2009, vol. 30, no. 4, p. 661–675. DOI: 10.1088/0143-0807/30/4/001

[11] BIOLEK, Z., BIOLEK, D., BIOLKOVÁ, V. SPICE modeling of memristive, memcapacitative and meminductive systems. In *Proceedings of the European Conference on Circuit Theory and Design (ECCTD'09)*. Antalya (Turkey), 2009, p. 249–252. DOI: 10.1109/ECCTD.2009.5274934

[12] RAK, A., CSEREY, G. Macromodeling of the memristor in SPICE. *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems*, 2010, vol. 29, no. 4, p. 632–636. DOI: 10.1109/TCAD.2010.2042900

[13] ABDALLA, H., PICKETT, M. D. SPICE modeling of memristors. In *Proceedings of the IEEE International Symposium on Circuits and Systems (ISCAS)*. Rio de Janeiro (Brasil), 2011, p. 1832 to 1835. DOI: 10.1109/ISCAS.2011.5937942

[14] BATAS, D., FIEDLER, H. A memristor SPICE implementation and a new approach for magnetic flux-controlled memristor modeling. *IEEE Transactions on Nanotechnology*, 2011, vol. 10, no. 2, p. 250–255. DOI: 10.1109/TNANO.2009.2038051

[15] PRODROMAKIS, T., PEH, B. P., PAPAVASSILIOU, C., TOUMAZOU, C. A versatile memristor model with nonlinear dopant kinetics. *IEEE Transactions on Electron Devices*, 2011, vol. 58, no. 9, p. 3099–3105. DOI: 10.1109/TED.2011.2158004

[16] KOLKA, Z., BIOLEK, D., BIOLKOVÁ, V. Hybrid modelling and emulation of mem-systems. *International Journal of Numerical Modeling: Electronic Networks, Devices and Fields*, 2012, vol. 25, no. 3, p. 216–225. DOI: 10.1002/jnm.825

[17] ESHRAGHIAN, K., KAVEHEI, O., CHO, K.-R., CHAPPELL, J. M., IQBAL, A., AL-SARAWI, S. F., ABBOTT, D. Memristive device fundamentals and modeling: Applications to circuits and systems simulation. *Proceedings of the IEEE*, 2012, vol. 100, no. 6, p. 1991–2007. DOI: 10.1109/JPROC.2012.2188770

[18] CORINTO, F., ASCOLI, A. A boundary condition-based approach to the modeling of memristor nanostructures. *IEEE Transactions on Circuits and Systems I*, 2012, vol. 59, no. 11, p. 2713–2726. DOI: 10.1109/TCSI.2012.2190563

[19] ASCOLI, A., CORINTO, F., SENGER, V., TETZLAFF, R. Memristor model comparison. *IEEE Circuits and Systems Magazine*, 2013, vol. 13, no. 2, p. 89–105. DOI: 10.1109/MCAS.2013.2256272

[20] PERSHIN, Y. V., DI VENTRA, M. Spice model of memristive devices with threshold. *Radioengineering*, 2013, vol. 22, no. 2, p. 485–489.

[21] KVATINSKY, S., FRIEDMAN, E. G., KOLODNY, A., WEISER, U. C. TEAM: ThrEshold Adaptive Memristor model. *IEEE Transactions on Circuits and Systems I*, 2013, vol. 60, no. 1, p. 211–221. DOI: 10.1109/TCSI.2012.2215714

[22] YAKOPCIC, C., TAHA, T. M., SUBRAMANYAM, G., PINO, R. E. Generalized memristive device SPICE model and its application in circuit design. *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems*, 2013, vol. 32, no. 8, p. 1201 to 1214. DOI: 10.1109/TCAD.2013.2252057

[23] ASCOLI, A., TETZLAFF, R., CORINTO, F., GILLI, M. PSpice switch-based versatile memristor model. In *Proceedings of the IEEE International Symposium on Circuits and Systems (ISCAS)*. Beijing (China), 2013, p. 205–208. DOI: 10.1109/ISCAS.2013.6571818

[24] BIOLEK, D., DI VENTRA, M., PERSHIN, Y. V. Reliable SPICE simulations of memristors, memcapacitors and meminductors. *Radioengineering*, 2013, vol. 22, no. 4, p. 945–968.

[25] PERSHIN, Y. V., DI VENTRA, M. Practical approach to programmable analog circuits with memristors. *IEEE Transaction on Circuits and Systems I*, 2010, vol. 57, no. 8, p. 1857–1864. DOI: 10.1109/TCSI.2009.2038539

[26] KVATINSKY, S., FRIEDMAN, E. G., KOLODNY, A., WEISER, U. C. The desired memristor for circuit designers. *IEEE Circuits and Systems Magazine*, 2013, vol. 13, no. 2, p. 17–22. DOI: 10.1109/MCAS.2013.2256257

[27] ASCOLI, A., TETZLAFF, R., CORINTO, F., MIRCHEV, M., GILLI, M. Memristor-based filtering applications. In *Proceedings of the 14th Latin American Test Workshop (LATW)*. Cordoba (Argentina), 2013, p. 1–6. DOI: 10.1109/LATW.2013.6562672

[28] XU, K. D., ZHANG, Y. H., WANG, L., YUAN, M. Q., FAN, Y., JOINES, W. T., LIU, Q. H. Two memristor SPICE models and their applications in microwave devices. *IEEE Transactions on Nanotechnology*, 2014, vol. 13, no. 3, p. 607–616. DOI: 10.1109/TNANO.2014.2314126

[29] BRAY, M. G., WERNER, D. H. Passive switching of electromagnetic devices with memristors. *Applied Physics Letters*, 2010, vol. 96, no. 7, p. 073504-1–073504-3. DOI: 10.1063/1.3299020

[30] WERNER, D. H., GREGORY, M. D. The memristor in reconfigurable radio frequency devices. In *Proceedings of the IEEE Antennas and Propagation Society International Symposium (APSURSI)*. Chicago (USA), 2012, p. 1–2. DOI: 10.1109/APS.2012.6349274

[31] SOMBRIN, J., MICHEL, P., SOUBERCAZE-PUN, G., ALBERT, I. Memristors as non-linear behavioral models for passive inter-modulation simulation. In *Proceedings of the 9th European Microwave Integrated Circuit Conference (EuMIC)*. Rome (Italy), 2014, p. 385–388. DOI: 10.1109/EuMIC.2014.6997873

[32] GREGORY, M. D., WERNER, D. H. Reconfigurable electromagnetics devices enabled by a non-linear dopant drift memristor. In *Proceedings of the IEEE Antennas and Propagation Society International Symposium (APSURSI)*. Memphis (USA), 2014, p. 563–564. DOI: 10.1109/APS.2014.6904612

[33] XU, K., ZHANG, Y., SPIEGEL, R. J., JOINES, W. T., LIU, Q. H. Memristor-based UWB antenna with reconfigurable notched band. In *Proceedings of Abstracts of the Progress In Electromagnetics Research Symposium*. Guangzhou (China), 2014, p. 1656.

[34] WU, H., ZHOU, J., LAN, C., GUO, Y., BI, K. Microwave memristive-like nonlinearity in a dielectric metamaterial. *Scientific Reports*, 2014, vol. 4:5499, p. 1–6. DOI: 10.1038/srep05499

[35] ENGELHARDT, M. *LTspice IV version 4.22s*. Linear Technology Corporation. [Online] Cited Jan 30, 2015. Available at: http://www.linear.com

[36] POZAR, D. M. *Microwave Engineering*. 4th ed. Hoboken: John Wiley & Sons, 2012. ISBN: 978-0-470-63155-3

[37] HONG, J.-S. *Microstrip Filters for RF/Microwave Applications*. 2nd ed. Hoboken: John Wiley & Sons, 2011. ISBN: 978-0-470-40877-3

[38] PETROVIĆ, V. V., TOŠIĆ, D. V., DJORDJEVIĆ, A. R. *Microwave Passive Circuits*. Belgrade (Serbia): University of Belgrade – School of Electrical Engineering, 2010. (in Serbian) [Online] http://www.etf.rs/etf_files/udzbenici/MPK_2010.pdf, ISBN: 978-86-7225-041-1

[39] WANHAMMAR, L. *Analog Filters Using MATLAB*. New York: Springer, 2009. ISBN: 978-0-387-92766-4, DOI: 10.1007/978-0-387-92767-1

[40] DJORDJEVIĆ, A. R., ZAJIĆ, A. G., STEKOVIĆ, A. S., NIKOLIĆ, M. M., MARIĆEVIĆ, Z. A., SCHEMMANN, M. F. C. On a class of low-reflection transmission-line quasi-Gaussian low-pass filters and their lumped-element approximations. *IEEE Transactions on Microwave Theory and Techniques*, 2003, vol. 51, no. 7, p. 1871–1877. DOI: 10.1109/TMTT.2003.814310

About the Authors ...

Milka POTREBIĆ was born in Belgrade, Serbia, in 1977. She received the B.S., M.S., and Ph.D. degrees in Electrical Engineering from the University of Belgrade, Belgrade, Serbia, in 2001, 2004, and 2009, respectively. In 2002, she joined the School of Electrical Engineering, University of Belgrade, as a Teaching and Research Assistant. She is currently an Associate Professor with the School of Electrical Engineering, University of Belgrade. She teaches classes in RF/microwave filters, microwave passive circuits, and electric circuit theory. Her research interests include analysis and design of RF and microwave circuits and systems, as well as signal processing. She is a member of the IEEE and Serbian Management Committee member of ICT COST Action IC1401 Memristors – Devices, Models, Circuits, Systems and Applications, MemoCiS, 2014–2018.

Dejan TOŠIĆ was born in Belgrade, Serbia, in 1957. He received the B.S., M.S., and Ph.D. degrees in Electrical Engineering from the School of Electrical Engineering, University of Belgrade, Belgrade, Serbia, in 1980, 1986, and 1996, respectively. He is currently a Full Professor with the School of Electrical Engineering, University of Belgrade. He teaches classes in RF/microwave filters, microwave passive circuits, microwave engineering, electromagnetics, and electric circuit theory. He is a co-author of the book *Filter Design for Signal Processing Using MATLAB and Mathematica* (Englewood Cliffs, NJ: Prentice-Hall, 2001, translated into Chinese by Publishing House of Electronics Industry, Beijing, China, 2004), a co-author of the book *WIPL-D Microwave: Circuit and 3D EM Simulation for RF & Microwave Applications* (Norwood, MA: Artech House, 2005), and a co-author of *SchematicSolver*, a software package for mixed symbolic-numeric analysis, processing, and design of analog and digital systems, distributed by Wolfram Research, Inc. at www.wolfram.com/products/applications/schematicsolver/. His research interests include symbolic computation, symbolic signal processing, RF and microwave filter design, and design of microwave passive circuits. He has published over 200 papers in these fields. Prof. Tošić was the recipient of the Teacher of the Year Award from the School of Electrical Engineering in 1992.