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An optoelectronic-based memristor emulator circuit with a rational memristance function

FATIH TULUMBACI[a,b,*], RESAT MUTLU[c]
[a]*Tekirdag Namik Kemal University, Electronics Department, Corlu Vocational School, 59860, Corlu, Tekirdag, Turkey*
[b]*Sakarya University, Department of Electrical Electronics Engineering, Institute of Natural Sciences, 54050, Serdivan, Sakarya, Turkey*
[c]*Tekirdag Namik Kemal University, Electronics and Communication Engineering Department, 59860, Corlu, Tekirdag, Turkey*

Memristor which has been claimed as the fourth fundamental circuit element in 1971 is a nonlinear circuit element having memory. Recently, an optoelectronics-based memristor emulator is reported in the literature. To the best of our knowledge, a memristor emulator with a rational memristance function has not been reported in literature yet. In this study, a memristor emulator which operates on optic principles or with optic circuit components with a rational memristance function is designed. The optoelectronic-based memristor emulator has two LEDs and an LDR. The emulator is made of off-the-shelf components and easy to build. Using simulations and experiments, it has been shown that the emulator is able to mimic memristor behavior well upto kilohertz region.

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Keywords: Memristor, Memristor Emulator, LED, Light Dependent Resistor, Optic Coupling, Optoelectronics

1. Introduction

In 1971, considering symmetry among circuit variables, Dr. Leon Chua has claimed that there should have been one more fundamental circuit element in addition to resistor, inductor and capacitor [1]. Chua described the circuit element as a power consuming charge-dependent nonlinear resistor. Due to its charge-dependency, it has a memory and that’s why it has been called as memristor (memory + resistor). The electrical resistance of a memristor which varies depending on the electric charge is also called memristance and can be expressed as the ratio of its voltage to its current. Memristive systems have been described and their equations and properties are given in 1976 by Chua and Kang [2]. They have shown that the memristors or the memristive systems fed by the AC signal source must have a zero-crossing frequency-dependent hysteresis curve. Memristor has remained as a theoretical circuit element for almost forty years. However, a TiO_2 thin-film sandwiched between the platinum contacts has been shown to behave as a memristor in 2008 [3], [4]. Following this discovery, memristor and memristive systems have become a hot research area. Once memristors become available in the market, they are expected to bring innovations in areas such as control, signal processing, programmable logic, filtering and communication electronic systems, memory chips, etc. due to their having memory [5]–[17]. Developing a memristor prototype is costly since these memristive elements are made in nano size. Therefore, memristor emulators are designed and widely used for proving concepts in memristor research and there are different types of memristor emulator circuits with very different topologies made using circuit components such as operational amplifiers, transistors, digital potentiometers, microprocessors, ADCs and analog multipliers in the literature [1], [7]–[9], [15]–[39]. Most emulator circuits are implemented using analog multipliers to obtain charge-controlled memristance or flux-controlled conductance [1], [7]–[9], [17]–[21], [37], [38]. The Memristor is a newly discovered element and its usage areas are still being investigated. Most of the researchers use simulations and/or memristor emulators to prove or demonstrate concepts in this area [1], [7]–[9], [15]–[39]. In 1971, Chua did not possess a memristor and he demonstrated the behavior of a memristor by means of using a memristor emulator [1]. Memristors have started coming out in the market however they are still not as cheap as off-the shelves electronics components [40], [41]. Therefore, the emulator circuits are still necessary and commonly used to experimentally discover their dynamics and how to exploit them efficiently and to verify the concepts of the memristive circuits [1], [7]–[9], [15]–[39].

Some memristor emulators are made of off-the shelf circuit components [19], [22], [37], [38]. Others can be made with using VLSI circuits [7], [17], [21], [29]. A memristor emulator with magnetic coupling is made in [42]. In [43], it was announced that there were light-emitting type memristors. An optoelectronics-based memristors are made using a light-dependent resistor in [44]. Such a circuit is used to make a chaos generator in [45]. It has been wrongfully claimed that the first optoelectronics-based memristor emulator was made in [46]. To the best of our knowledge, a memristor emulator with a rational memristor function using either optic principles or made with optic circuit components do not exist in literature yet. In this work, an optoelectronic-based memristor emulator with a rational memristor function which has two LEDs and an LDR is designed. Using simulations and experiments, it has been shown that the emulator is able to mimic memristor behavior and it performs well.

This work is organized as the follows. In the second section, the memristor emulator designed in this study is introduced, its state-space models are given and the emulator is simulated using Simulink® toolbox of MATLAB™. An optocoupler is made using two LEDs and an LDR and its characteristics required to model the emulator are obtained. In the third section, the behavior of the memristor at different operating voltages and frequencies is examined. The experimental results are also interpreted in this section. This study has been finished with the conclusions section.

2. Material and method

2.1. Memristor emulator circuit

A memristor emulator is a circuit which behaves as if a memristive system or a memristor. In this work, the optoelectronics-based memristor emulator circuit is designed with easy to find, cheap and easy to apply circuit components. The circuit diagram of the memristor emulator to be implemented in this study is shown in Fig. 1.

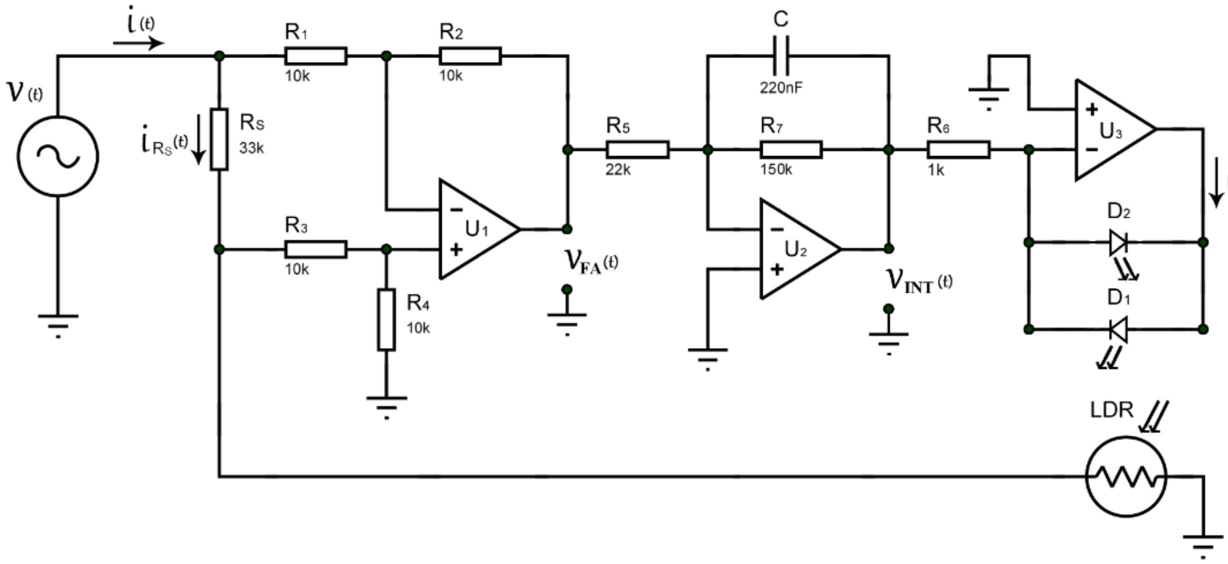


Fig. 1. Memristor emulator circuit schematic

$v(t)$ is the input voltage of the memristor emulator. $i_{R_S}(t)$ which is the current of the resistor R_S in the circuit is directly proportional to the memristor emulator input current $i(t)$. The $i_{R_S}(t)$ current is amplified using by means of the differential amplifier and then it is integrated using an inverting integrator as shown in Fig. 1. This integrator is connected to an inverting opamp having two anti-parallel LEDs D_1 and D_2 as feedback elements and the resistor R_6 as the input resistor. The current of the resistor R_6 is proportional to the output voltage of the integrator. $i_{LED}(t)$ is also proportional to integral of The current of the resistor R_6. Depending of polarity of the current $i_{LED}(t)$, either D_1 or D_2 are starts conducting. The current $i_{LED}(t)$ is also proportional to integral of $i(t)$. The LDR and the LEDs are shown in Fig. 1 placed in a box which does not take light from outside. The LDR is only illuminated with the LEDs. Therefore, the resistance of the LDR resistor R_{LDR} depends on the emitted light by the LEDS or the total currents of the anti-parallel connected LEDs $i_{LED}(t)$. In other words, it is possible to change the value of the LDR resistor R_{LDR} by changing the light emitted proportionally to the current of the feedback LEDs. The input resistance of the emulator circuit depends on the LDR resistor R_{LDR} which is dependent on the integration of the emulator current $i(t)$. Therefore, the circuit behaves as a memristor since the its input resistance or memristance depends on the integration of the emulator current $i(t)$ which can be called as the memristor emulator charge $q(t)$.

The circuit given in Fig. 1 can be analyzed now. The following equations can be written when using Kirchhoff's laws and assuming opamps are ideal. The voltage of the LDR resistor is

$$V_{LDR} = V_{in} \frac{(R_3 + R_4)R_{LDR}}{(R_3 + R_4)R_{LDR} + R_S\left[(R_3 + R_4) + R_{LDR}\right]} \tag{1}$$

Output voltage of the differential amplifier made with the opamp U_1 is

$$V_{FA}(t) = \left(\frac{R_4}{R_3 + R_4}\right)\left(1 + \frac{R_2}{R_1}\right)V_{LDR} - \frac{R_2}{R_1}V(t) \tag{2}$$

Output voltage of the integrator made with the opamp U_2 is

$$V_{INT}(t) = \frac{R_1 R_S}{(R_1 + R_S)R_5 C}\int_{-\infty}^{t} i(t)dt \tag{3}$$

The current of the anti-parallel connected LEDs fed through resistor R_6 is

$$i_{LED}(t) = \frac{R_1 R_S}{(R_1 + R_S)R_5 R_6 C}\int_{-\infty}^{t} i(t)dt \tag{4}$$

The charge of the memristor emulator is described as the integral of the input current with respect to time if the opamp U_2 is not operating in saturation;

$$q(t) = \int_{-\infty}^{t} i(t)dt \tag{5}$$

If γ is defined as

$$\gamma = \frac{R_1 R_S}{(R_1 + R_S)R_5 R_6 C} \tag{6}$$

The current of the anti-parallel connected LEDs can be written as

$$i_{LED}(t) = \frac{R_1 R_S}{(R_1 + R_S)R_5 R_6 C}q(t) = \gamma q(t) \tag{7}$$

The current of the memristor emulator is found as

$$i(t) = \left(\frac{(R_1 + R_S)\left((R_3 + R_4)R_{LDR} + R_S\left((R_3 + R_4) + R_{LDR}\right)\right) - \left(R_1(R_3 + R_4) + R_4 R_S\right)R_{LDR}}{R_1 R_S\left((R_3 + R_4)R_{LDR} + R_S\left((R_3 + R_4) + R_{LDR}\right)\right)}\right)V(t) \tag{8}$$

The memristance or the input resistance of the memristor emulator is given as

$$M(q) = \frac{V(t)}{i(t)} = \frac{R_1 R_S\left((R_3 + R_4)R_{LDR} + R_S\left((R_3 + R_4) + R_{LDR}\right)\right)}{(R_1 + R_S)\left((R_3 + R_4)R_{LDR} + R_S\left((R_3 + R_4) + R_{LDR}\right)\right) - \left(R_1(R_3 + R_4) + R_4 R_S\right)R_{LDR}} \tag{9}$$

As can be seen from Eq. (9), the resistance of the emulator depends on the value of the LDR resistor, R_{LDR}, which depends on the currents of the anti-parallel connected LEDs and the dependency is to be modeled in the next section to show the emulator resistance is a rational function of the emulator charge.

2.2. The LED and LDR current-voltage characteristic

The experimental setup in Fig. 2 was used to measure the resistance value of the LDR resistor depending on the light intensity emitted from the anti-parallel connected LEDs being in the memristor emulator's circuit. Both LDR and LED currents are measured using ampermeters and recorded as a table. The resistor R is connected in series to anti-parallel connected LEDs to protect them from having overvoltages or destructive high currents.

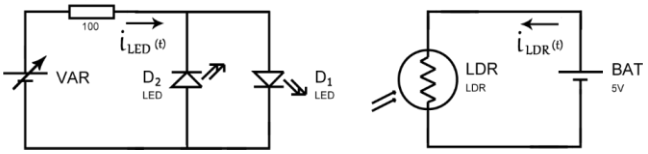


Fig. 2. The LED and LDR current-voltage characteristic test setup

In the first step in the experiment, the voltage source to which the LEDs are connected is set to 0V (for $i_{LED} = 0$). The regulated power supply is then gradually increased and the LDR current and the total current of the LEDs are recorded. During the experiment, a fixed 5V DC voltage was applied to the LDR. In the second stage, the polarity of the voltage supply feeding the LEDs is reversed. The currents of the LDR and the LEDs are recorded again by adjusting the negative voltage applied by the power supply. The currents obtained with this experiment are plotted in Fig. 3.

The LDR resistance is calculated as follows using the LDR current measured and the applied voltage of 5 Volts:

$$R_{LDR} = \frac{V_{LDR}}{I_{LDR}} = \frac{5}{I_{LDR}} \tag{10}$$

The LDR resistance variation with respect to the current of the anti-parallel connected LEDs obtained via the experimental setup are shown in Fig. 4.

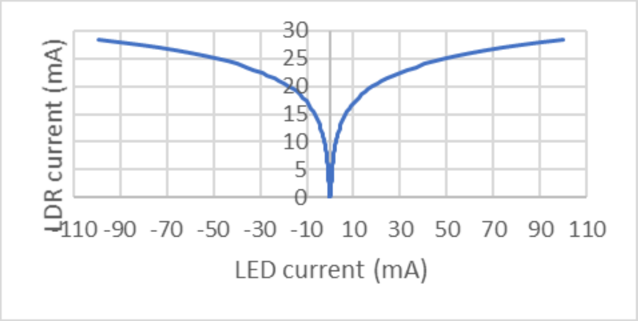


Fig. 3. The LDR current versus the current of the anti-parallel connected LEDs

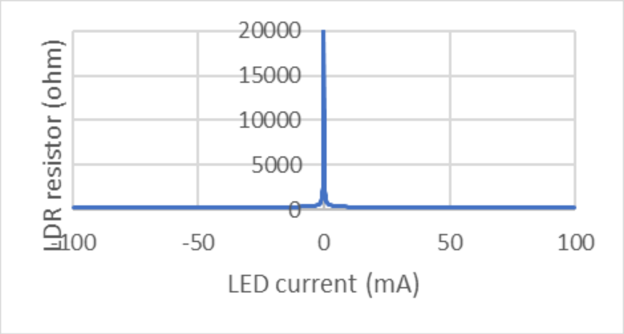


Fig. 4. The LDR resistance versus the anti-parallel LED current(s)

The LDR resistance R_{LDR} as a function of anti-parallel connected LED current(s) is found by using the least squares method. The curve-fitting function found is given as equation 11 and the coefficients in equation 11 are given in Table 1.

$$R_{LDR} = a_6 \left|i_{LED}\right|^6 + a_5 \left|i_{LED}\right|^5 + a_4 \left|i_{LED}\right|^4 + a_3 \left|i_{LED}\right|^3 + a_2 \left|i_{LED}\right|^2 + a_1 \left|i_{LED}\right| + R_0 \tag{11}$$

Table 1. The calculated coefficients of the LDR resistance equation

The Curve-fitting Coefficients	**Its value**
R_0	4142
a_1	-1349
a_2	125
a_3	-4.8
a_4	8.8×10^{-2}
a_5	-75.2×10^{-5}
a_6	2.4×10^{-6}

When equation 11 is submitted to equation 9, the input resistance of the memristor emulator can be written as

$$M(q) = \left(\frac{k_1 + \left[a_6 \left|i_{LED}\right|^6 + a_5 \left|i_{LED}\right|^5 + a_4 \left|i_{LED}\right|^4 + a_3 \left|i_{LED}\right|^3 + a_2 \left|i_{LED}\right|^2 + a_1 \left|i_{LED}\right| + R_0 \right] R_S \left(k_2 + k_3 + 1\right)}{R_S k_4 + \left[a_6 \left|i_{LED}\right|^6 + a_5 \left|i_{LED}\right|^5 + a_4 \left|i_{LED}\right|^4 + a_3 \left|i_{LED}\right|^3 + a_2 \left|i_{LED}\right|^2 + a_1 \left|i_{LED}\right| + R_0 \right] \left[k_5 - k_2 - k_3 - k_6\right]} \right) \tag{12}$$

The parameters in equation 12 is given in Table 2.

Table 2. The coefficients used in the memristance equation

Parameter	**Value**
k_1	$R_S(R_3+R_4)$
k_2	R_1R_3
k_3	R_1R_4
k_4	$(R_1+R_S)(R_3+R_4)$
k_5	$(R_1+R_S)(R_3+R_4+R_S)$
k_6	R_4R_S

If equation 7 is submitted to equation 11, the memristor emulator's memristance is found as

$$M(q) = \left(\frac{k_1 + \left[a_6 \gamma^6 q(t)^6 + a_5^{-5} \left|\gamma^5 q(t)^5\right| + a_4 \gamma^4 q(t)^4 + a_3 \left|\gamma^3 q(t)^3\right| + a_2 \gamma^2 q(t)^2 + a_1 \left|\gamma q(t)\right| + R_0 \right] R_S \left(k_2 + k_3 + 1\right)}{R_S k_4 + \left[a_6 \gamma^6 q(t)^6 + a_5^{-5} \left|\gamma^5 q(t)^5\right| + a_4 \gamma^4 q(t)^4 + a_3 \left|\gamma^3 q(t)^3\right| + a_2 \gamma^2 q(t)^2 + a_1 \left|\gamma q(t)\right| + R_0 \right] \left[k_5 - k_2 - k_3 - k_6\right]} \right) \tag{13}$$

Eq. (13) is rational function of the memristor emulator charge.

2.3. Memristor Emulator Circuit MATLAB™ Simulink® Model

In this section, Simulink® toolbox of MATLAB™ program is used to simulate the memristor emulator. The state-space equations of the designed memristor emulator are given below.

$$v(t) = M(q)i(t) \tag{14}$$

$$\frac{dq}{dt} = i(t) \tag{15}$$

$$M(q) = \left(\frac{k_1 + \left[a_6\gamma^6 q(t)^6 + a_5^{-5}\left|\gamma^5 q(t)^5\right| + a_4\gamma^4 q(t)^4 + a_3\left|\gamma^3 q(t)^3\right| + a_2\gamma^2 q(t)^2 + a_1\left|\gamma q(t)\right| + R_0\right] R_S (k_2 + k_3 + 1)}{R_S k_4 + \left[a_6\gamma^6 q(t)^6 + a_5^{-5}\left|\gamma^5 q(t)^5\right| + a_4\gamma^4 q(t)^4 + a_3\left|\gamma^3 q(t)^3\right| + a_2\gamma^2 q(t)^2 + a_1\left|\gamma q(t)\right| + R_0\right]\left[k_5 - k_2 - k_3 - k_6\right]} \right) \tag{16}$$

The Simulink block diagram of the memristor emulator is shown in Fig. 5.

The memristor emulator charge and memristance are shown in Figs. 6 and 7 respectively when it is simulated with a sinusoidal signal with a frequency of 18 Hz and a peak-to-peak amplitude of 2 V. Variation of charge is shown in Fig. 6. The memristance varies between 350 Ω and 770 Ω as shown in Fig. 7. When simulated using the Simulink®, the memristor model has given acceptable results similar to those of a real memristor. The Simulink model of the memristor emulator possesses three basic fingerprints, the features, that a memristor or memristive system must possess as defined in [47]. Developed for the memristor emulator, this simulink model demonstrates charge dependency and hysteresis properties such as the memristive system. The results of the simulation obtained conform to the characteristics of a memristor defined in [1], [2] and [47].

Chua and Kang have shown that memristors or memristive systems fed by the AC current source must have a zero-crossing hysteresis loop and they have theoretically shown that the memristor's hysteresis curve gradually gets narrower and will exhibit resistor-like behavior as the frequency increases [2]. Fig. 8 shows the behavior of the memristor emulator simulated by the sinusoidal signal at a peak-to-peak voltage of 2V and a frequency of 18Hz. Hysteresis curve and current-voltage curves are examined using simulations. It is seen that the simulated curves are similar to those that can be obtained with an ideal memristor. It conforms to the definition of Chua and Kang's memristive systems [2]. It is also the first of three fingerprints that a memristor or a memristive system must possess described in [47]. The current and voltage of the memristor emulator both become zero at the same time is the second fingerprint of a memristive system.

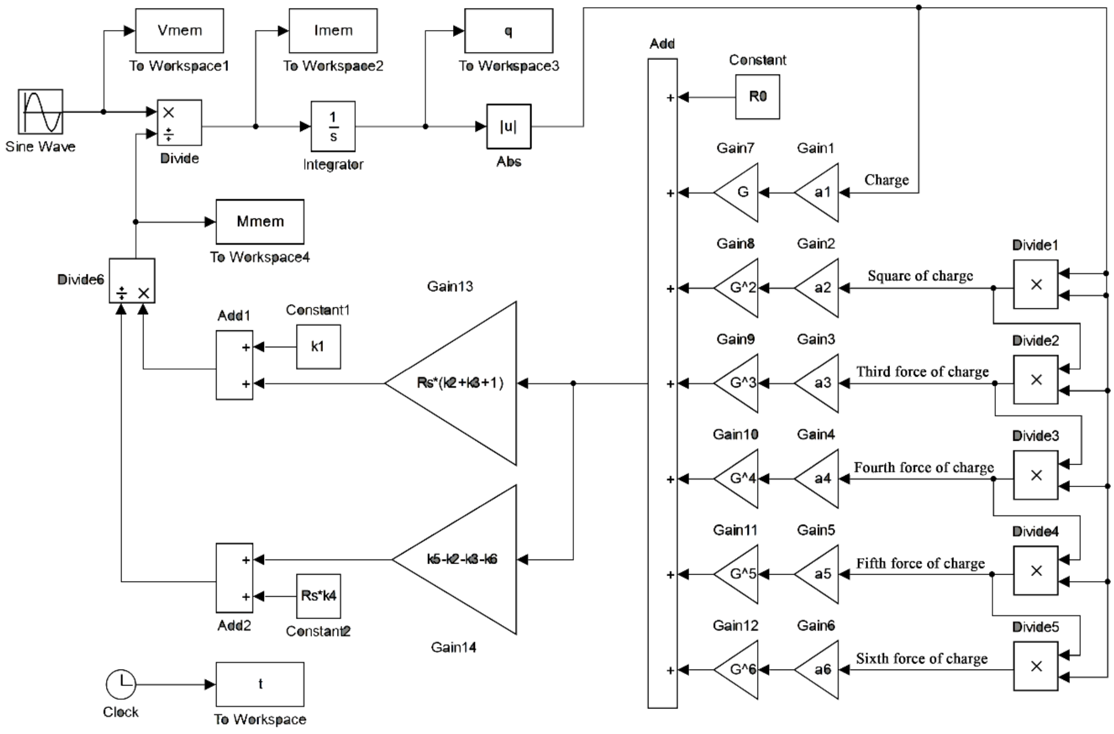


Fig. 5. Simulink^{TM} block diagram of the Memristor emulator circuit

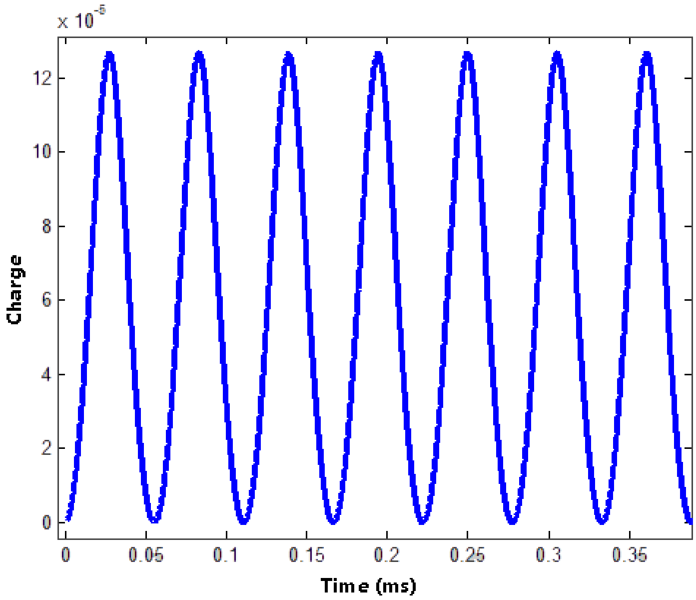


Fig. 6. Simulated memristor emulator charge versus time when it is fed with a sinusoidal voltage source of a peak-to-peak voltage of 2 V and a frequency of 18 Hz

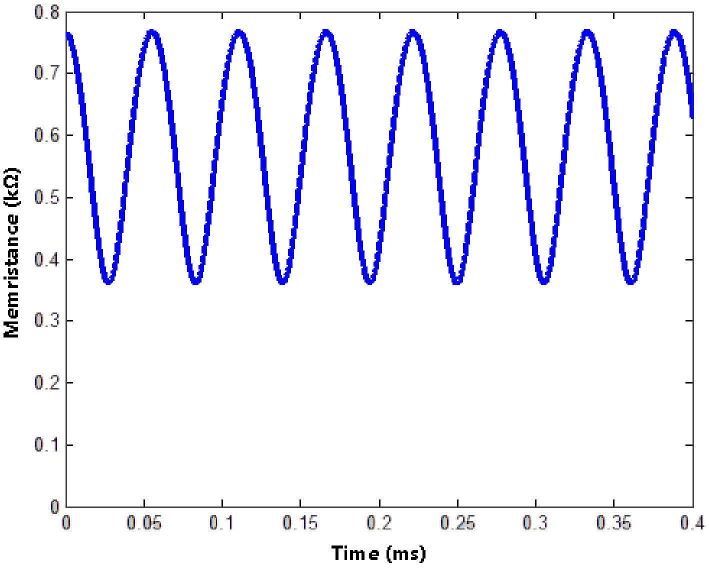
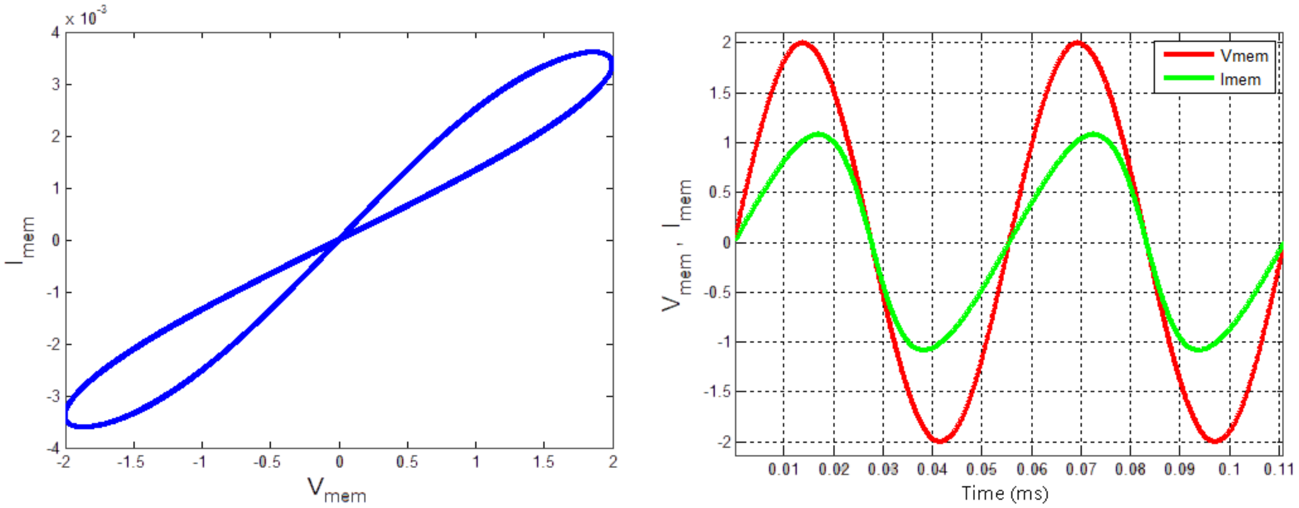


Fig. 7. Simulated memristor emulator memristance versus time when it is fed with a sinusoidal voltage source of a peak-to-peak voltage of 2 V and a frequency of 18 Hz

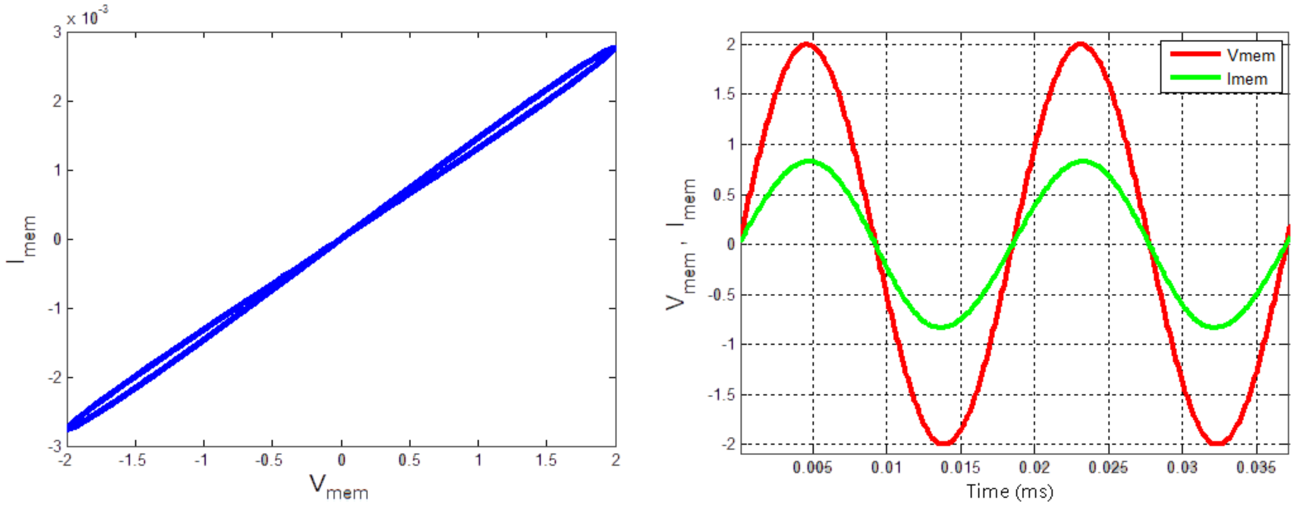
Fig. 9 shows the behavior of the memristor emulator simulated by a sinusoidal signal of a peak-to-peak voltage 2V and a 54 Hz frequency. It appears that the area of the hysteresis curve gets narrowed due to the increase in frequency. Chua and Kang have theoretically predicted this situation in [2]. The third one of the three fingerprints that the memristor or memristive systems should have is a narrowing frequency dependent hysteresis curve when the operation frequency increases as described in [47]. The simulink model for the designed memristor emulator meets the criteria.

The behavior of the memristor emulator simulated by the sinusoidal signal at 150 Hz frequency and with a peak-to-peak voltage of 2V is shown in Fig. 10. The current and voltage curves are in sinusoidal form and the hysteresis curve appears to be linear like resistance. At very high frequencies, a memristor or memristive system should behave as a LTI resistor as described in [47].



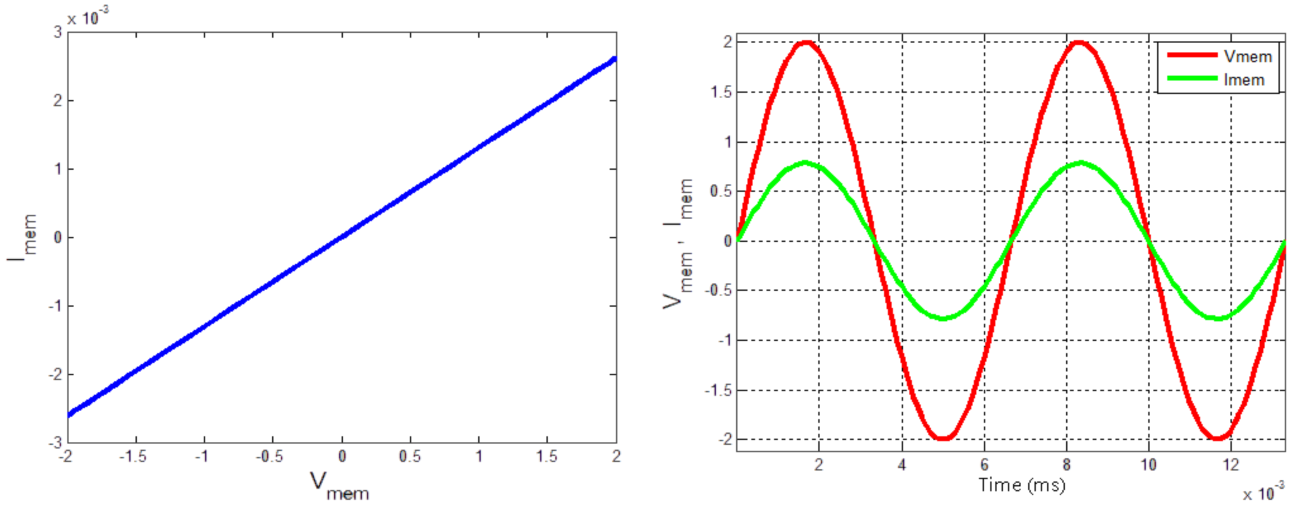
(a) (b)

Fig. 8. When the memristor emulator is fed with a sinusoidal voltage of a peak-to-peak voltage of 2V and a frequency of 18 Hz: (a) The current-voltage characteristic of the memristor emulator and (b) The current and voltage of the memristor emulator vs. Time (color online)



(a) (b)

Fig. 9. When the memristor emulator is fed with a sinusoidal voltage of a peak-to-peak voltage of 2V and a frequency of 54 Hz: (a) The current-voltage characteristic of the memristor emulator and (b) The current and voltage of the memristor emulator vs. Time (color online)



(a) (b)

Fig. 10. When the memristor emulator is fed with a sinusoidal voltage of a peak-to-peak voltage of 2V and a frequency of 150 Hz: (a) The current-voltage characteristic of the memristor emulator and (b) The current and voltage of the memristor emulator vs. Time (color online)

3. Experimental results

An LDR is a circuit component which is quite sensitive to sunlight or ambient light. The changes in the ambient light in addition to LEDs' light affects the LDR resistance. Therefore, an optocoupler is made. A closed box is used to prevent the LEDs-LDR optocoupler system from being affected by daylight. Fig. 11 shows the optocoupler circuit schema and its arrangement in a box. The hand-made optocoupler box is shown in Fig. 12. This totally enclosed box is painted by black color to prevent the effects of the external light and the internal light reflections that may come into play. The memristor emulator circuit is assembled on the protoboard and is also shown in Fig. 12.

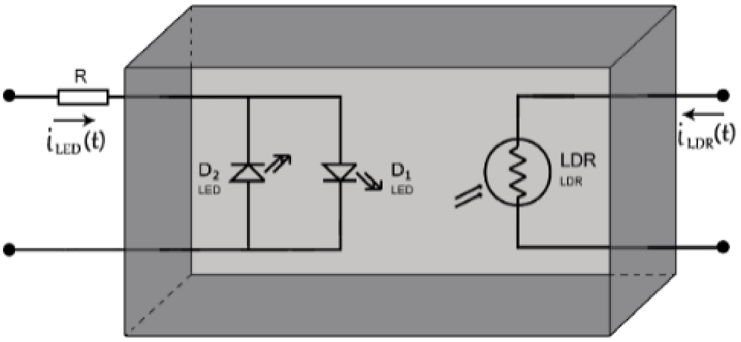
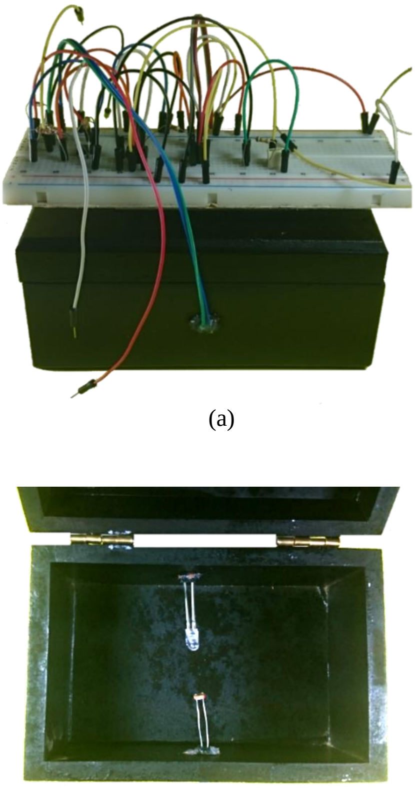


Fig. 11. Optocoupler circuit of the Memristor emulator

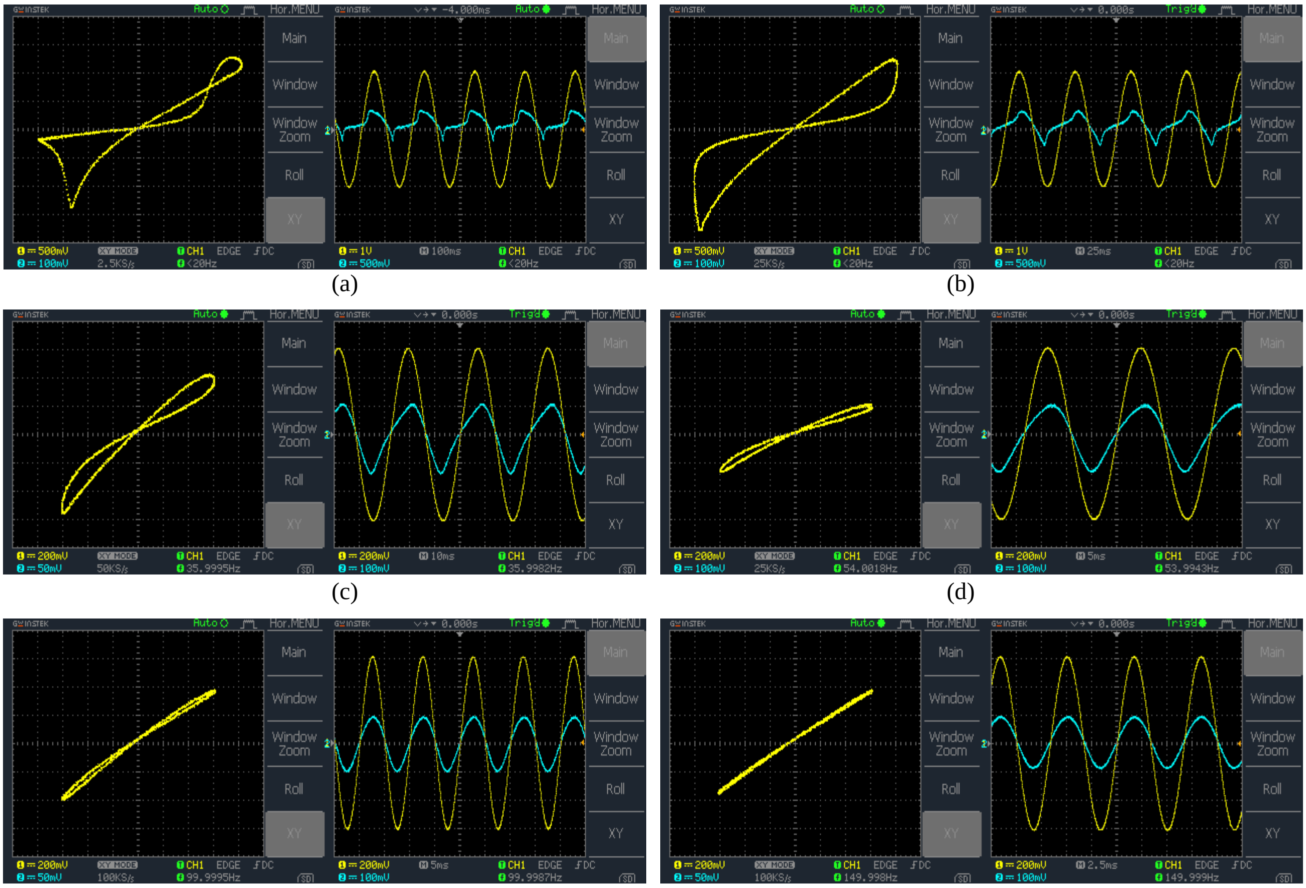

(a)

(b)

Fig. 12. The hand-made optocoupler box: (a) external view of the optocoupler box and the emulator circuit (b) internal view of the optocoupler box (color online)

Experimental results obtained at different frequencies are given in Fig. 13. At 5Hz, it is seen that a different hysteresis curve is obtained from other frequencies. Chua and Kang have said that such zero-crossing hysteresis curves are possible to exist in memristive systems in [2]. Abdalla and Pickett also obtained a similar curve with the SPICE model of memristor they have made [48]. Considering the experimental results obtained at the test frequencies, it can be seen that the obtained results are zero-crossing hysteresis curves. If the frequency increases, the area of the hysteresis curve gets narrower and, at high frequencies, is transformed into a line as a linear time-invariant resistor would have. Therefore, the designed memristor emulator carries three fingerprints that the memristor or memristive systems must possess and successfully emulates a memristor [47].

Experiments were carried out at 1, 3, 5 and 20 kHz frequencies with a peak-to-peak voltage of 1V to analyze the high frequency behavior of the designed memristor emulator. The hysteresis curves obtained as a result of the experiments are shown in Fig. 14. As can be seen in the hysteresis curves, the memristor emulator maintains the memristive system property with the signals whose operation frequency is upto 3 kHz. This means that the circuit can emulate a memristor up to this frequency. At frequencies of 5 kHz and above it seems that the memristor emulator can not provide a zero-crossing hysteresis curve. Therefore, this designed memristor emulator does not behave like the memristive system at frequencies of 5 kHz and above and can not mimic the behavior of the memristor. It is shown that this memristor emulator has three fingerprints that must be possessed by memristors and performs well upto up to 3 kHz.

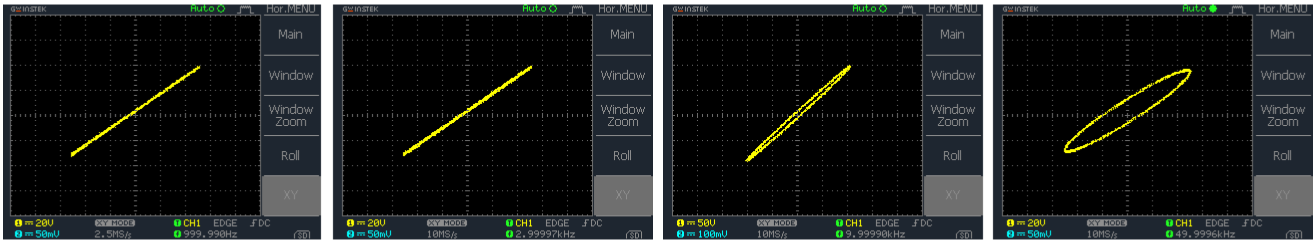


(a) (b)

(c) (d)

(e) (f)

Fig. 13. When a peak-to-peak 4V sinusoidal voltage is applied to the memristor emulator, its current and voltage vs. time and its hysteresis curve at (a) 5Hz, (b) 18Hz, (c) 36Hz, (d) 54Hz, (e) 100Hz, (f) 150Hz (color online)



(a) (b) (c) (d)

Fig. 14. The hysteresis curves of the memristor emulator when it is fed by a sinusoidal source with a peak-to-peak voltage of 1V and a frequency of (a) 1 kHz, (b) 3 kHz, (c) 5 kHz and (d) 20 kHz (color online)

4. Conclusions and recommendations

In this work, an optoelectronic-based memristor emulator with a rational memristance function is built using two LEDs and an LDR. This circuit does not need expensive circuit elements such as analog multipliers and easier to build. To the best of our knowledge, there is no other memristör emulator with a fractional memristance function given in the literature other than the one examined in this study. An optocoupler system is created using two LEDs and an LDR in a closed box and is used in the memristor emulator. A mathematical model for the hand-made optoelectronic system is done. State-space equations of the emulator are also given. Then, the emulator circuit is simulated using Simulink. The emulator circuit is set up on a board and tested using sinusoidal voltage. The behavior of the emulator circuit at different frequencies has been examined. It has been shown that the designed memristor emulator behaves as a memristor and this emulator performs well up to around 3 kHz. Even if it is not a real memristor, it has been shown experimentally that this circuit has all three fingerprints of a memristor given in [47] and can mimic the behavior of an ideal memristor such as charge dependency, zero-crossing hysteresis loop, and frequency dependency. This emulator has a very rich dynamic (hysteresis) behavior in addition to mimicking the behaviors given in [37, 47]. The memristor emulator is not affected much by the DC offset current as in [37] and is able to produce a steady hysteresis loop due to having a rational memristance function. Therefore, it has been demonstrated that the memristor emulator performs well.

Since the LDR is a resistor and the LEDs are placed as feedback elements of the opamp amplifier, the emulator does not have the threshold voltage as the ones given in memristors [22, 43]. Direction dependent memristive system behavior can also be obtained by using LEDs of different characteristics. The emulator in [44] has an odd memristance function whileas the one given here has an even memristance function. According to the way the LEDs are placed inside the box, the characteristic of the optocoupler and, therefore, the memristor emulator can be changed. The system in [43] is a LED system which behaves as a memristive system in ultra-low frequencies whose the memristor function is not properly given. However, the emulator examined in this study operates at higher frequencies and it is also shown how its memristance function can be obtained.

The memristor emulator can be used in chaotic circuits, analog amplifiers, oscillators, etc. Furthermore, this emulator is suitable for use in memcapacitor and meminductor emulators which can be made using a memristor emulator and a gyrator circuit.

Although the emulator circuit presented in this work has a higher operating frequency than the one given in [37,44], it is not suitable for studying the behavior of the memristor at above 3 kHz which is defined with the operating frequency of an LDR since LDRs cannot be operated well at kHz frequencies [49]. We suggest using high frequency response optoelectronic elements such as photodiodes or phototransistors instead of an LDR to obtain higher operating frequencies as future work as done in [44], [45]. It is shown in [50-55] that memristor-based chaotic circuits can be used in secure communications. If the proposed circuit is modified with anti-parallel connected photodiodes instead of an LDR, it can also be used in chaotic communication systems due to the high frequencies photodiodes can operate. Artificial neurons can also be made using such an emulator. Especially due to its ability to be coupled with light, it can facilitate the construction of coupled neurons such as Hindmarsh–Rose neurons. The memristor emulator designed here can also be used in memristor research to prove concepts and memristor education due to its easiness to build. Different memristance functions can also be obtained by changing the circuit connections of the memristor emulator.

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[*] Corresponding author: ftulumbaci@nku.edu.tr