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MIXED SIGNAL LETTER

# A new floating memristor emulator and its application in frequency-to-voltage conversion

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**Abstract** In this paper a new circuit for practical emulation of a floating memristor is presented. The circuit is simple, flexible and built around the current-feedback operational-amplifier and avoids the use of analog-to-digital and digital-to-analog converters and the analog multiplier. The circuit is simpler than the very few available similar circuits. The application of the proposed floating memristor emulator in designing an FM-to-AM converter confirms the functionality of the proposed circuit. Experimental results are included.

**Keywords** Memristor · Current-feedback operational-amplifier · Frequency-to-voltage converter

## 1 Introduction

Since its inception several emulators have been presented for the grounded memristor; see for example [1] and the references cited therein. However, only few floating memristor emulators are available in the literature [2–6]. The circuit proposed in [2], [6] uses four current-feedback operational-amplifiers (AD844) configured as plus-type second-generation current-conveyors (CCII+s), a four-quadrant analog multiplier (AD633), a grounded capacitor and a number of grounded and floating resistors. In [3] the authors improved the floating memristor circuit proposed in [4] to achieve the current equality by adding two current conveyors. The complete circuit reported in [3] uses two operational amplifiers (TL084), two current-feedback operational amplifiers (AD844) configured as plus-type second-generation current-conveyors (CCII + s), a four-quadrant analog multiplier (AD633), a floating capacitor and a number of floating and grounded resistors. The circuit proposed in reference [5] comprises a differential amplifier, a unity-gain voltage inverter, an operational-amplifier based integrator with a floating capacitor, an analog-to-digital converter (ADC), a resistive digital-to-analog converter, a number of diodes and grounded and floating resistors. The practical implementation of this circuit requires five UA741 operational amplifiers, one AD7821 ADC, four 1N4151 diodes, six ALD1106PBL NMOS transistors in addition to the resistors and capacitor. It appears, therefore, that there is a need for a simpler floating memristor emulator using off-the-shelf components. The major intention of this paper is to present such a circuit.

## 2 Proposed circuit

The proposed floating memristor circuit is shown in Fig. 1. The input voltage will produce a current through the resistance $R_1$ given by

$$i_{R_1} = (v_{inp} - v_{inn})/R_1 \qquad (1)$$

Assuming ideal CFOAs with $v_X = v_Y, i_Z = i_X, v_W = v_Z, i_Y = 0$ [7], this current will flow outward from terminal X of CFOA1 and inward into terminal X of CFOA3. This current will be replicated in terminal Z of CFOA1 where it will be integrated by the capacitor $C_1$ to produce a voltage given by

$$v_{Rp} = \frac{1}{C_1}\int \frac{v_{inp} - v_{inn}}{R_1} dt \qquad (2)$$

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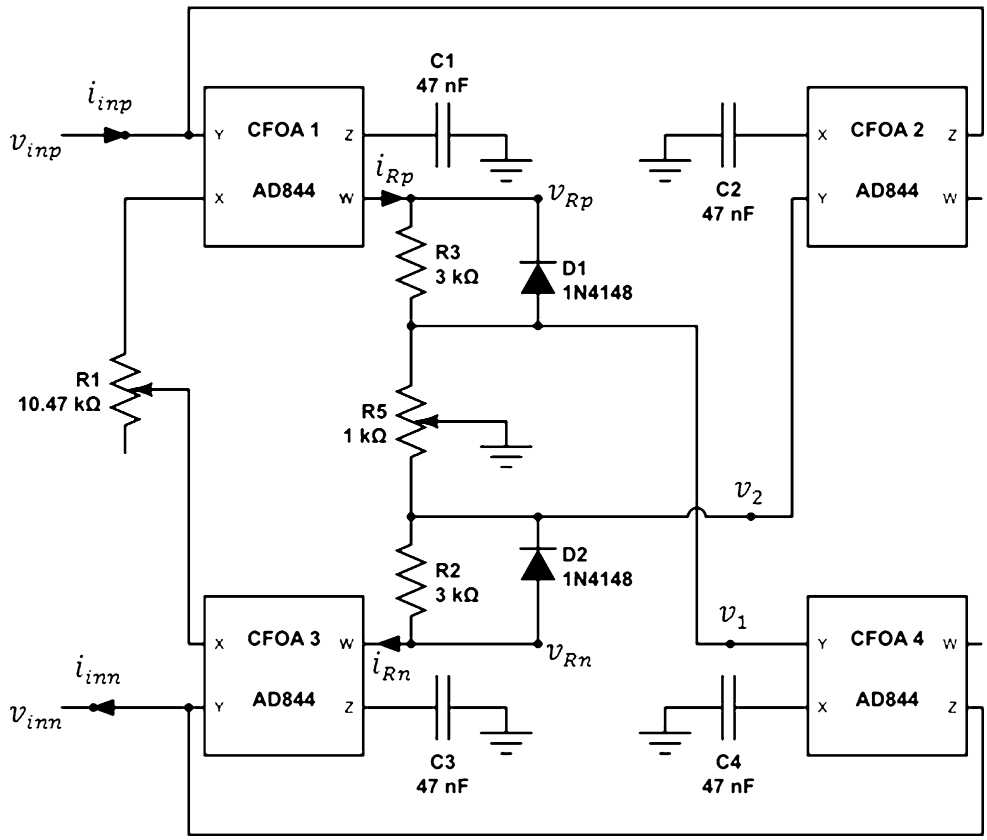


**Fig. 1** The proposed floating memristor emulator 1

This voltage will be replicated in terminal W of CFOA1 and will produce an outward current, from terminal W of CFOA1, $i_{Rp}$, through the parallel combination of $R_3$ and $D_1$ in series with the upper part of the potentiometer $R_5$. This current can be expressed as

$$i_{Rp} = \frac{v_{Rp}}{R_{5upper} + R_{eq1}} \tag{3}$$

In Eq. (3) $R_{5upper}$ is the resistance of the upper part of the potentiometer $R_5$ and $R_{eq1}$ is a nonlinear resistance that depends on the status of the diode $D_1$. Obviously, the voltage at terminal Y of the CFOA4 will depend on the status of the diode $D_1$. This voltage can be expressed as

$$v_1 = \frac{v_{RP} R_{5upper}}{R_{5upper} + R_{eq1}} \tag{4}$$

The voltage $v_1$ will be replicated in terminal X of the CFOA4 and will be differentiated by the capacitor $C_4$. Thus, the outward current in the lower input terminal will be given by

$$i_{inn} = C_4 \frac{dv_1}{dt} \tag{5}$$

In a similar way the current $i_{R_1}$ will be replicated in the terminal Z of CFOA3 and will be integrated by the capacitor $C_3$ to produce a voltage given by

$$v_{Rn} = \frac{-1}{C_3} \int \frac{v_{inp} - v_{inn}}{R_1} dt \tag{6}$$

In Eqs. (2) and (6) the voltage $v_M = v_{inp} - v_{inn}$ is the differential input voltage. The voltage $v_{Rn}$ will be replicated in terminal W of CFOA3 and will produce an inward current $i_{Rn}$ through the parallel combination of $R_2$ and $D_2$ in series with the lower part of the potentiometer $R_5$. This current can be expressed as

$$i_{Rn} = \frac{-v_{Rn}}{R_{5lower} + R_{eq2}} \tag{7}$$

In Eq. (7) $R_{5lower}$ is the resistance of the lower part of the potentiometer $R_5$ and $R_{eq2}$ is a nonlinear resistance that depends on the status of the diode $D_2$. The voltage at terminal Y of CFOA2 can be expressed as

$$v_2 = \frac{v_{Rn} R_{5lower}}{R_{5lower} + R_{eq2}} \tag{8}$$

In Eq. (8) $R_{5lower}$ is the resistance of the lower part of the potentiometer $R_5$ and $R_{eq2}$ is a nonlinear resistance that depends on the status of the diode $D_2$. This voltage will be replicated in terminal X of CFOA2 and will be differentiated by the capacitor $C_2$. Thus, the inward current in the upper input terminal will be given by

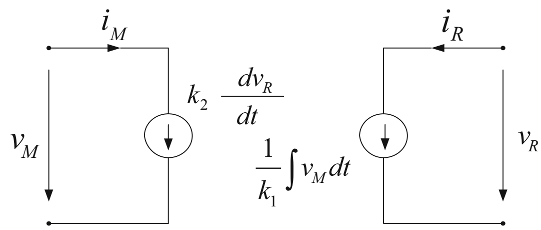


**Fig. 2** Memristor model based on Eqs. (11) and (13)

$$i_{inp} = -C_2 \frac{dv_2}{dt} \tag{9}$$

Assuming that the diodes $D_1$ and $D_2$ are identical, $C_1 = C_3 = C_i$, $C_2 = C_4 = C_d$, $R_2 = R_3$, and the potentiometer $R_5$ is midway with $R_{5upper} = R_{5lower} = \frac{1}{2}R_5$, then $R_{eq1} = R_{eq2} = R_{eq}$, $v_{Rn} = -v_{Rp} = -\frac{1}{2}v_R$, $i_{Rn} = i_{Rp} = i_R$ and $v_2 = -v_1$. Combining Eqs. (1) and (6) the voltage $v_R = v_{Rp} - v_{Rn}$ can be expressed as

$$v_R = v_{Rp} - v_{Rn} = \frac{2}{C_i R_1} \int v_M dt \tag{10}$$

Using Eqs. (2), (3), (6) and (7) the current $i_R = i_{Rp} = i_{Rn}$ can be expressed as

$$i_R = \frac{1}{k_1} \int v_M dt \tag{11}$$

In Eq. (11) the parameter $k_1$ is given by

$$k_1 = \frac{(R_5 + 2R_{eq})C_i R_1}{2} \tag{12}$$

Also combining Eqs. (5) and (9) the input current can be expressed as

$$i_M = i_{inp} = i_{inn} = k_2 \frac{dv_R}{dt} \tag{13}$$

In Eq. (13) the parameter $k_2$ is given by

$$k_2 = \frac{C_d R_5}{R_5 + 2R_{eq}} \tag{14}$$

Equations (11) and (13) can be represented by Fig. 2. Figure 2 corresponds to a voltage-controlled memristor where the voltage exciting the memristor $v_M$ is integrated in the form of a current $i_R$. This current is converted via a nonlinear resistor to voltage $v_R$, and this voltage is transformed by differentiation to the memristor current $i_M$. In terms of the mutator concept, it is the memristor-resistor mutator of type 2 realization 2 [8]. Now if the input voltage $v_M$ is a sinusoidal voltage of the form $v_M = V_M \sin \omega t$ then using Eq. (11) the current $i_R$ will be given $i_R = \frac{1}{k_1 \omega} V_M \cos \omega t$. This current will be converted to a voltage via a nonlinear resistance to produce a voltage $V_R = i_R R_{eq}$ where $R_{eq}$ is the effective equivalent resistance that depends on the status of the diodes $D_1$ and $D_2$. Using Eq. (13) this voltage will produce the current $i_M = \frac{k_2}{k_1} R_{eq} V_M \sin \omega t$. Thus, the effective resistance of the memristor will be given by

$$M = \frac{k_1}{k_2} \frac{1}{R_{eq}} \tag{15}$$

Equation (15) implies that the memristor is equivalent to a resistor which is dependent on $R_{eq}$. Since $R_{eq}$ can acquire two different values depending on the status of the diodes $D_1$ and $D_2$ then Eq. (15) implies that the memristor can acquire two values of resistance.

It is worth mentioning here that Eqs. (11) and (13) were obtained assuming that the CFOAs are ideal, the diodes $D_1$ and $D_2$ are identical, the two capacitances $C_1$ and $C_3$ are equal, the two resistances $R_2$ and $R_3$ are equal, the two capacitances $C_2$ and $C_4$ are equal and the potentiometer $R_5$ is midway. Obviously any deviation from these assumptions will result in unequal values for the inflowing current and the output current and the circuit may not be emulating a floating memristor. However, for any practical use of the proposed floating memristor emulator careful adjustment of the involved components, by using variable capacitors and resistors rather than fixed-value ones, can compensate any possible inequalities and nonidealities and result in a floating memristor emulator with equal inflowing and output currents. In some cases recourse to adding small variable resistors in series with the diodes may be helpful.

Compared with the floating memristor emulator circuits proposed in [2–6], the proposed circuit uses four AD844 CFOAs. In this regard it is similar to the circuits proposed in [2], [6]. However, the proposed circuit avoids the use of the AD633 multiplier reported in [2], [6]. Instead it uses simple Ge diodes to provide the necessary nonlinear function. While the circuit reported in [3] uses only two AD844 CFOAs, it requires two additional TL084 operational amplifiers and an AD633 multiplier. The floating memristor circuit proposed in [4] uses two operational amplifiers and one multiplier circuit. However, as mentioned by the authors of [4] this memristor emulator cannot guarantee the equality between the inflowing and output currents of its two terminals. Thus, the circuit proposed in [4] is incomplete and is not supposed to be applied to simulate canonical memristor. The floating memristor circuit proposed in [6] uses two operational amplifiers, a single inverting unity gain amplifier, a 6-bit analog-to-digital converter (ADC), a 6-bit resistive digital-to-analog (RDAC) converter in addition to a number of diodes. Thus, it appears that, compared to the already existing circuits, the proposed circuit of Fig. 1 uses less number of active elements. This may lead to less power consumption. Another advantage of the proposed circuit of Fig. 1 is the use of grounded capacitors. In this regard it is similar to the circuits reported in [2], [6]. The major drawback of the proposed circuit of Fig. 1 is the use of four equal-value capacitors instead of one capacitor as in the circuits reported in [2–6] in addition to two equal-value resistors. Thus, any mismatch in the values of the capacitors and/or resistors may affect the performance of the circuit. However, with the availability of variable resistors and capacitors it may be easy to compensate for the effect of mismatch between the capacitors, resistors and the non-idealities of the CFOAs.

## 3 Experimental results

This section will present the experimental verification of the circuit of Fig. 1 followed by its application in designing an FM-to-AM converter. The circuit was realized using the component values shown in Fig. 1. The results obtained are shown in Figs. 3, 4 and 5. Inspection of Figs. 3(b), 4(b) and 5 clearly shows the frequency dependence of the memristance of the floating memristor circuit of Fig. 1. It is obvious that as the frequency increases from 1.1 to 6.0 kHz, the floating memristor tends to behave as a normal resistor. Inspection of Figs. 3(a) and 4(a) clearly shows that an injected sinusoidal voltage will produce a distorted input current. This is due to the nonlinear resistance of the floating memristor of Fig. 1.

The functionality of the proposed floating memristor emulator circuit of Fig. 1 was tested by using it in FM-to-AM conversion. The proposed circuit is shown in Fig. 6. The circuit of Fig. 6 is a simple frequency-dependent variable-gain inverting amplifier exploiting to advantage the frequency dependence of the memristance. Assuming

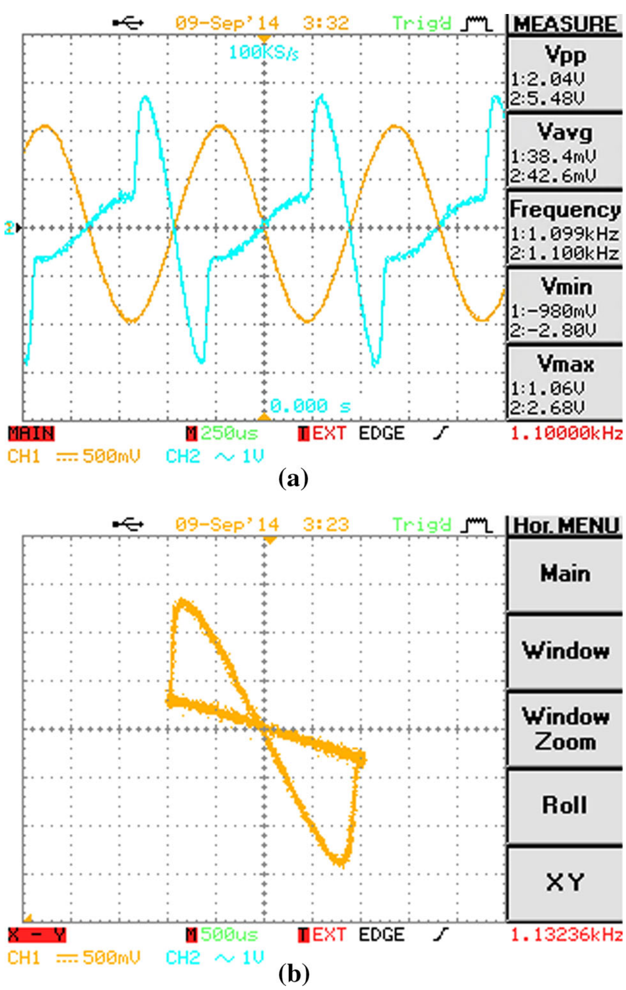


**Fig. 3** The behaviour of the floating memristor emulator circuit of Fig. 1 at 1.1 kHz (**a**) waveforms of the injected voltage $V_M$ (pure sinusoidal signal) and resulting current $I_M$ (**b**) current ($I_M$)–voltage ($V_M$) characteristic with a relatively large difference in the memristor resistance values

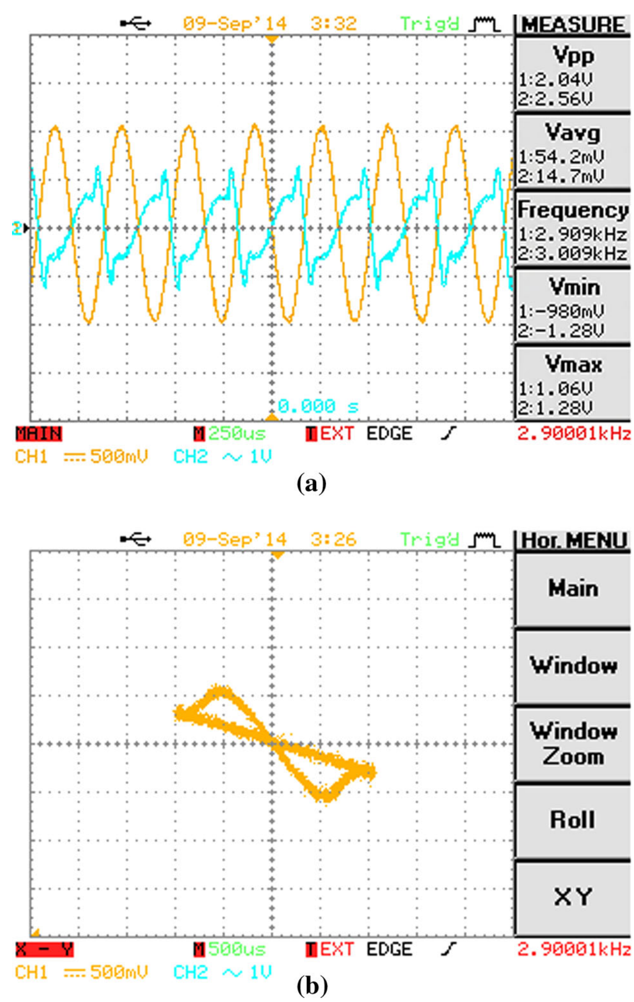


**Fig. 4** The behaviour of the emulator circuit of Fig. 1 at 2.9 kHz (**a**) waveforms of the injected voltage $V_M$ (pure sinusoidal signal) and resulting current $I_M$ (**b**) current ($I_M$)-voltage ($V_M$) characteristic with a relatively small difference in the memristor resistance values

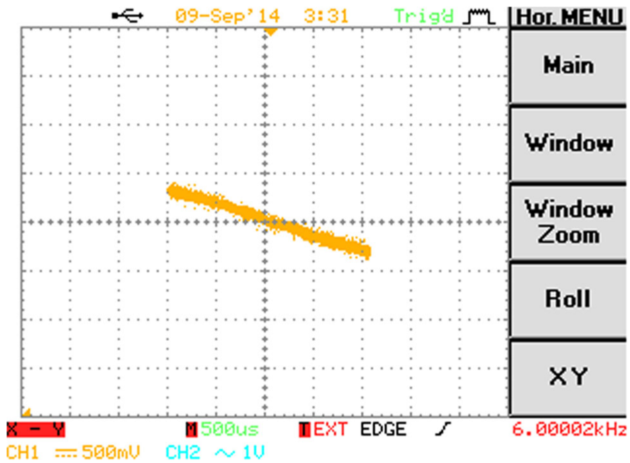


**Fig. 5** The behaviour of the emulator circuit of Fig. 1 at 6.0 kHz where the memristor is acting as a simple resistor with one value of the resistance

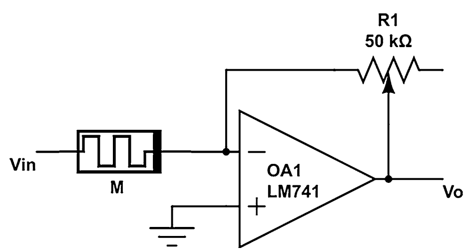


**Fig. 6** A inverting amplifier circuit using the proposed floating memristor circuit of Fig. 1

ideal operational amplifier, the gain of the inverting amplifier of Fig. 6 can be expressed as

$$G = -\frac{R_1}{R_M} \quad (16)$$

Since the resistance of the memristor $R_M$ is frequency dependent, then the gain of the circuit of Fig. 6 will be dependent on the input frequency. Thus, if an FM signal is applied at the input then it is conjectured that the output will be an AM signal.

The circuit of Fig. 6 was tested using an FM input signal formed of a carrier of frequency equal to 2 kHz, a modulating frequency of 100 Hz and frequency deviation of 900 Hz. To verify the operation of the proposed FM-to-AM converter the output of the circuit of Fig. 6 was applied to an envelope detector formed of diode $D_1$, resistor $R_3$ and capacitor $C_1$ followed by a lowpass filter formed of the operational amplifier OA2, resistors $R_4$ and $R_5$, capacitors $C_2$ and $C_3$ and the variable resistor $R_8$ as shown in Fig. 7. The results obtained are shown in Figs. 8, 9 and 10. Figure 8 shows the input FM signal and the output AM signal measured at the output of the operational amplifier OA1 of Fig. 7. Figure 8 clearly shows that the FM input was converted to an AM as conjectured. Figure 9 shows the modulating signal at the output of the envelope detector. Figure 10 shows the original FM signal and the recovered modulating signal. Inspection of Figs. 8, 9 and 10 clearly shows that the proposed FM-to-AM converter works as conjectured and exploited to advantage the frequency dependence of the floating memristor emulator of Fig. 1. It is worth mentioning that while the circuit of Fig. 6 was used here to prove the functionality of the proposed floating memristor emulator of Fig. 1, the circuit can be used as an effective FM-to-AM converter especially at very low frequencies when the conventional methods, usually based on detuning an LC circuit, may require relatively large values of capacitors and/or inductors.

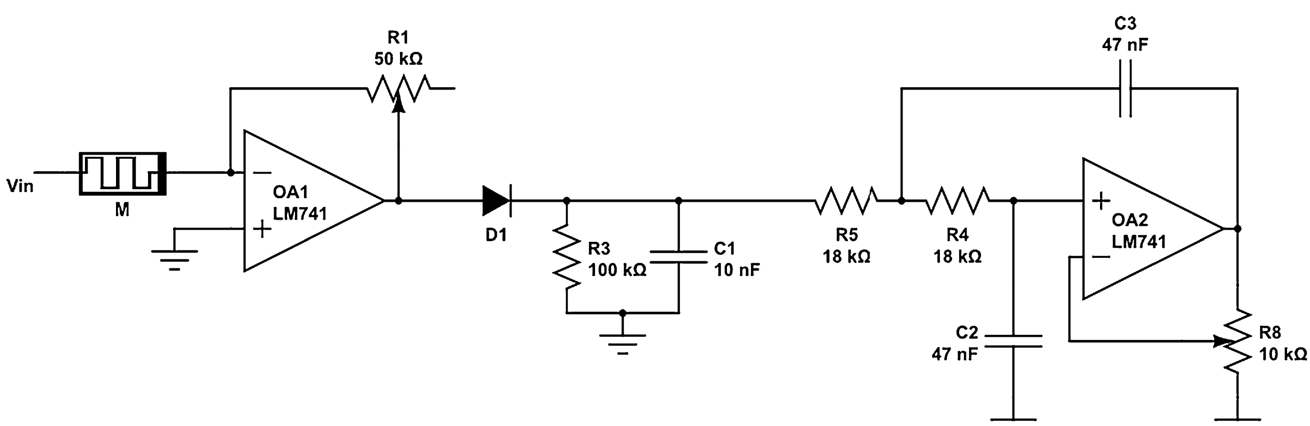


**Fig. 7** An FM demodulator using the floating memristor model. D1 is germinum doide, R1 = 6.25 kΩ, R4 and R5 = 18 kΩ

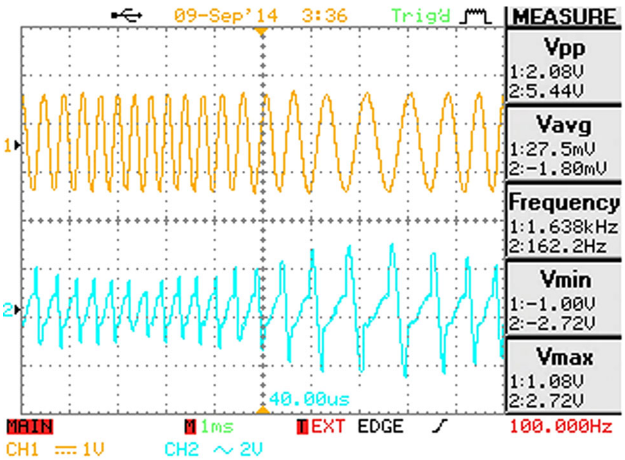


**Fig. 8** The input FM signal (*up*) and the converted AM signal (*down*) at the input of the envelope detector

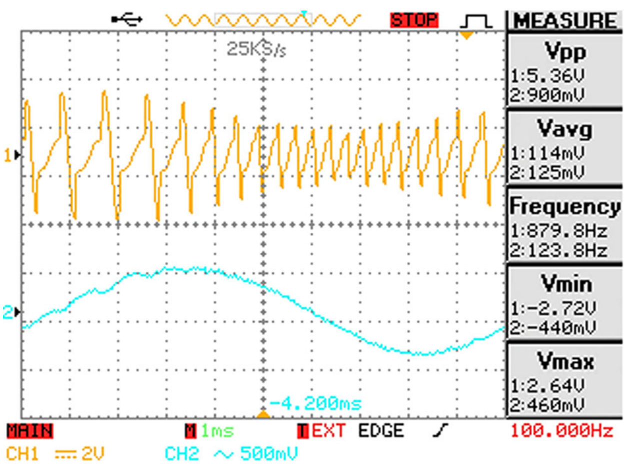


**Fig. 9** The converted AM signal (*up*) and the output demodulated signal at the output of the lowpass fierlt (*down*)

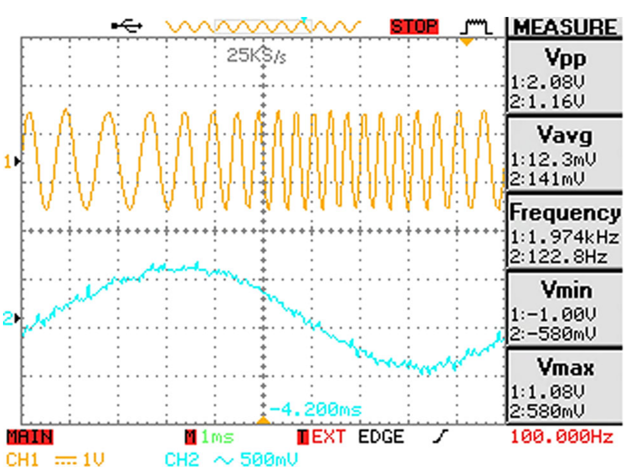


**Fig. 10** The input FM signal (*up*) and the output modulaing signal at the output of the lowpass filter (*down*)

## 4 Conclusion

In this paper a new circuit implementation for the floating memristor has been presented. The proposed circuit uses grounded capacitors and CFOAs in addition to combinations of diodes and resistors to provide the required nonlinearity and time constants. The proposed circuit avoids the use of analog multipliers, ADCs and RDACs. This would result in less power consumption, cost reduction and ease of implementation. The proposed circuit has been used for converting an FM signal to AM signal by exploiting to advantage the frequency-dependence of the memristance. The results obtained confirmed the functionality of the proposed floating meristor circuit.

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