**Measured Behaviour of a Memristor-Based Tuneable Instrumentation Amplifier**

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A memristor-based tuneable instrumentation amplifier whose gain value can be adjusted by memristor is implemented and measured. Whilst memristive devices are suitable for implementing reconfigurable circuit designs, their non-linear characteristic and parasitic capacitance can impact performance. In this work, an instrumentation amplifier is built on breadboard using off-the-shelf OpAmps and packaged memristor devices and its performance is assessed. Results are compared with an identical design that preplaces memristors with resistors (losing reconfigurability in the process), to reveal the effects arising from the memristor’s characteristics. Effects on frequency response, common mode rejection ratio (CMRR) and total harmonic distortion plus noise (THD+N) are observed. We show that the memristor-based instrumentation amplifier begins to be affected by the non-linearity of the device only when the base OpAmps have a THD value below 0.3%, which is in the range normally expected of low-distortion amplifiers. The bandwidth of the instrumentation amplifier is limited by the parasitic capacitance of memristors, and CMRR has small variation when using memristor to replace the original gain resistor. THD+N value is large comparing with identical design, but it is also found that by applying multiple memristors the increasing of THD+N can be relieved.

*Introduction:* Memristors are a two-terminal non-volatile passive circuit elements, whose resistance depend on the history of current or voltage applied on them [1]. Their low power operation, small size, ability to store multi-bit information [2] and other characteristics such as their simple, two terminal structure [3] make them good tools for implementing reconfigurability on-chip. However, the characteristics of memristors need to be carefully considered when designing circuits and systems. Typical areas that require attention include avoiding potentially catastrophic overvoltages and the memristors’ typical non-linear current-voltage curves that cause static resistance to vary with bias voltage [4]. Circuits where the voltage applied on the memristor remains fixed (e.g. is a standardised square-wave pulse) will be affected less than circuits where biasing conditions are more free. Moreover, fundamentally metal-oxide-metal stacks memristors act as metal-insulator-metal (MIM) capacitors, potentially adding substantial parasitic capacitance and affecting high-frequency operation. A more complete model of the memristor is thus a resistor in parallel with a capacitor [5], as shown in Fig 1 (a), where the value of the parasitic capacitance in mainly decided by the material, structure and size of the memristor [6].

In this paper, TiOx/Al2O3 memristor devices introduced within an instrumentation amplifier, adding reconfigurability, and test the actual behaviour of memristor in real device. The memristive devices replace some of the gain setting resistors (see Eq.1) to render gain a tuneable parameter. Previous attempts included using CMOS structures to replace the gain resistor Rg from Fig 1 (b), rendering gain tuneable via a tuning signal [7], [8], or controlling the gain with currents as per the current-mode instrumentation amplifier structure [9]. The system was implemented on breadboard, memristor array was set in package and programmed by measurement instrument Arc Two. The gain and frequency response of the amplifier with varying memristor resistance levels was measured, to test the performance of memristor as tuneable resistor and the effect of parasitic capacitor. The CMRR and THD+N of the circuit with gain resistor and memristor at the same value were also measured, to research on the effect that memristor gives to the signal. We discovered that the parasitic capacitance of memristor affects the gain bandwidth of the instrumentation amplifier, but does not have much influence in CMRR characteristics. The non-linear current-voltage (I-V) function of memristor strongly increases the THD+N value, but measurement also shew that applying multiple memristors in the amplifier can relieve the increasing of signal harmonic distortion.

*Background and Methodology:* The schematic of the memristor-based instrumentation amplifier implemented in this work is shown in Fig 1 (b) and follows the standard structure [10]. The gain of the instrumentation amplifier can be written as:

 $Gain\left(Av\right)=\frac{V\_{out}}{V\_{in}}=(1+\frac{2R\_{1}}{R\_{g}})×\frac{R\_{3}}{R\_{2}}$ (1)

where Rg is the resistance of the gain resistor, or more generally the static resistance of the element sitting in the position (here the memristor). In this work all the resistors are set to the same value.



**Fig 1** **(a)** *Lumped element model of memristor.* **(b)** *Schematic of memristor based tuneable instrumentation amplifier.*

The memristors used here are TiOx/Al2O3 bi-layer devices [11], with electrode area 10$×$10µm2 and active layer (the material between the electrodes) thickness of 4nm. Multiple memristors are used in the measurement, whose resistances are in the total range of [10, 100]kΩ, each of them has vary centre frequencies and can change its resistance in the range of about 10kΩ. Based on [6], the cut off frequency for TiOx/Al2O3 memristor with resistance range from 10kΩ to 100kΩ is in the range of 0.1-1MHz. To ensure that the main gain roll-off effect does not arise from the OpAmps’ characteristics we used TLV2372 OpAmps with gain-bandwidth of 3MHz (typ. voltage gain 110dB). The entire system was prototyped on breadboard under a power supply of 5V. Transient simulation with measurement of current supply was run. By multiplying the fixed supply voltage and measured current value, power dissipation is computed as average of 20 operating cycles.

External instruments “ArC One” and “ArC Two” (ArC instruments, UK) are used to program the memristor [12]. These fundamentally act as source-meter units co-integrated with a routing network with ArC One operating in pseudo-parallel and ArC Two in true-parallel mode. Importantly, ArC Two is used as follows: Initially the memristive packages is connected to the internal electronics of ArC Two, which allows us to adjust the test memristors to specific resistance level by applying high voltage pulses, and measure their I-V curves. Once at an appropriate and known level, the instrument passes control of the device to the breadboard-based instrumentation amplifier. On-board RC filters ensure that charge injection effects that have been previously found to alter the state of memristive devices during such switch-overs are sufficiently mitigated. Then the main experiments are carried out and finally, the devices are switched back to internal ArC Two control to check that the “before” and “after experiment” I-V curves do not show significant alteration. Memristive devices were converged to the desired states using automated algorithms similar in spirit to [13] that seek to change resistance states gently, protecting the memristor devices and slowing down ageing. As the programming of memristor is set to have a tolerance, the memristor resistance values can have 1kΩ to 3kΩ error compare with the desired values. Finally, for the memristors used in this project it was confirmed that the device can maintain a stable resistance level (no resistive switching present) for biasing voltages below ±1.2V (checked by applying multiple pulse of length 100ms at said voltage), we can loosely define as the switching threshold of the device. Hence the pulse voltages chosen to program the memristors are in the [0.6, 2]V range. The 2V upper limit is set to prevent overvoltage-induced memristor failure. As OpAmps are in follower configuration, the voltage across the position Rg is a smoothed version of the input voltage. Hence the memristor are biased invasively, and there is no obvious mechanism by which accidental programming can occur.

*Results:* Based on Eq. 1, when all the resistors are set with resistance 75kΩ, and the memristor-defined Rg ranges in [30, 70]kΩ, the gain of the instrumentation amplifier varies in [9.95, 15.56]dB. The gain response of the instrumentation amplifier for different values of Rg is shown in Fig 3. Measurement with Rg implemented by a discrete resistor at 30kΩ and 75kΩ are also given for comparison.

It can be observed that the curves for Rg 30kΩ (resistor) and 27kΩ (memristor) match very well at low frequency. It is found that the -3dB cut-off frequency of the memristor curve is slightly higher than the resistor curve, providing a slight extension to the bandwidth and a slightly cleaner transition into the roll-off region. Both these phenomena can be explained by considering that the impedance magnitude of the memristive device starts to tail off around 100kHz due to its parasitic shunt capacitance as seen in Fig 2. Similarly for the resistors (albeit for lower parasitic capacitance value). This causes Rg to drop and gain to increase before the TLV OpAmps’ natural roll-off takes over. At high frequencies, when the parasitic capacitor dominates memristor impedance, all memristors show the same low impedance value. This is a direct result of their common parallel plate geometry (same plate size and same dielectric thickness). By ~1MHz, all memristors feature practically the same impedance value (within 8%). This result illustrates the importance of being aware of parasitic capacitance and the role that device geometry plays in setting device characteristics. It suggests device area as an independent engineering parameter in AC applications for devices where it has been shown that device area generally does not directly affect resistive switching characteristics because the conduction mechanism is localised in a filament-like region. This is especially true of metal-oxide devices of the “electrochemical metallisation” (ECM) variety [14]. However, overall layout geometry may still indirectly affect device performance: for instance the width of the electrodes used to access the device may introduce series resistance and dull the impact of programming pulses onto the device proper.

CMRR results of the instrumentation amplifier with 30kΩ resistor and different values of memristors at 1kHz were measured. CMRR values are similar in all the cases, which is around 80dB, including similar degradation over simulation results. Simulation was done in TINA-TI, with manufacturer-provided micromodels of the TLV2372 OpAmps, ideal resistor and ideal capacitor based memristor lumped element model. The degradation is caused by the mismatch of the real resistor elements and OpAmps. This result is expected since the voltage applied across the memristor remains largely unchanged regardless of common mode, hence mostly eliminating it as a source of additional error.

Fig 4 shows the THD+N of the instrumentation amplifier with different values of memristor and with Rg implemented by 30kΩ resistor at 1kHz. The THD+N values roughly increase with the increasing of memristor values, but there are also some exceptions in Fig 5, which are the curves of memristor 25kΩ and 56kΩ. This is because there are multiple memristors been used in the measurement, and different memristors have different I-V curves. Memristors can have the same resistance at a specific voltage, but their resistance will vary at other voltages if they had different I-V curves [15]. The THD+N values of the instrumentation amplifier with gain resistor and memristor at input AC amplitude 30mV are 1.1% and [1.8, 2.1] % range. These values are large compared to simulation results using the manufacturer’s OpAmp model, and may be caused by the electronic noise in the laboratory environment, possibly affecting probes and oscilloscope. This hypothesis seems to be corroborated by the THD+N curve of the resistor first reduces with the increasing input signal magnitude, allowing it to overpower noise-induced distortive effects, and then increases after input signal amplitude higher than 200mV. We note that at 200mV input signal THD+N is very close to baseline (0.1%). By 300mV input signal the amplifier starts to saturate and observed THD+N increases. By comparison, the memristor design’s THD+N increases faster and nearly does not benefit from a THD+N reduction during the amplitude sweep. The higher distortion is expected given the non-linearity in the I-V function of the memristive device. What was less obvious a priori was that at very small input signal the overall levels of THD+N are nearly high enough to hide the non-linearity in the IV of at least the particular flavour of memristive devices used in this work. We can expect that to be both a result of higher noise levels reducing the competitiveness of the resistor-based approach and perhaps more importantly the increasing “linearization” of the memristive device as we enter truly small-signal regime. It is therefore reasonable to expect that for <10mV signal amplitudes (as may be the case for electrophysiological or other extremely fine signals) the distortion induced by memristor-based amplification may not be a limiting factor, even in systems with employing hefty noise-mitigation.

To test the signal distortion in the circuit with multiple memristor devices, resistors R1 and R1’ in Fig 1 (b) are replaced by memristors, and the 3 memristors at positons Rg , R1 and R1’ are set to have approximately the same value. As comparisons, results for amplifier with one memristor are also measured, with resistors R1 and R1’ have the same value as gain memristor. To research on the influence of memristor resistance to the signal distortion, in this experiment the memristors are chosen to have extreme values, which are 10kΩ and 100kΩ. Measurement results show the triple memristors amplifier has the similar gain and CMRR as the instrumentation amplifier which has three resistors with same value. Fig 5 shows the THD+N results. The memristors been used in (3$×$10kΩ) test have accurate values [8, 10, 9] kΩ, and memristors for (3$×$100kΩ) test have accurate values [97, 101, 99]kΩ. It can be observed that THD+N values of using 3 memristors are smaller than using 1 memristor. As the resistance of memristor floats with voltage changes, when there is only one memristor, the ratio between R1 resistor and Rg memristor changes with time, hence the signal distortion large. However, when using memristors take the place of R1 resistors, resistances of the 3 memristors vary at the same time, the ratio between R1 and Rg changes smaller, which improves the THD+N value. The THD+N of using 3$×$100kΩ memristors is smaller than using 3$×$10kΩ memristors. This is because in these tests R1 memristors’ values have small differences, and the (difference/ required resistance) ratio is larger with smaller memristor value.

Table 1 lists the performance characteristics of the memristor based instrumentation amplifier and other tuneable instrumentation amplifiers in the literature. Compared with other designs, the memristor-based amplifier designed in this work has comparable base characteristics such as bandwidth, CMRR and power dissipation, especially given its implementation using off-the-shelf OpAmps, but also critically good gain range of the back of what represents a relatively modest memristive device ON/OFF ratio compared to what has been reported in the literature: An ~2.63 ON/OFF ratio leads to an ~7.5dB voltage gain ratio whereas the literature reports memristive devices with 103 [16] or even 106 ON/OFF ratios. We cannot comment on the specific IV and switching characteristics of those devices in this work. The current implementation of this design was on breadboard, which means that it carries too much stray capacitance to be competitive as it stands, but with integration on chip it should be able to become competitive in the niche of "non-volatile gain control". In the Table 1, reference [9, 17, 18] are all volatile gain control, which need continue voltage / current supplies to maintain their stages, in which case the non-volatile control is the benefit of this design.

**Table 1.** Comparison between memristor based tuneable instrumentation amplifier with other tuneable instrumentation amplifier designs.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Ref. | This work | [9] | [17] | [18] |
| Gain (dB) | 9.5-16  | 20-40 | 13-17 | 4.7-18 |
| Max. to Min. Gain Ratio (dB) | 7.5  | 20 | 4 |  13.3 |
| Bandwidth (Hz) | 500k | 10k | 83.75M | 3-14.8M |
| CMRR (dB) | 90 | 44.4-49 | 96 | 51.2 |
| Power Dissipation (W) | 7.33m | 72-385n | 4.43m | 864u |

*Conclusion:* This work sought to understand the effects of using real memristive devices in the usually high-gain and good precision instrumentation amplifier configuration. It was concluded that i) The parasitic capacitance of the memristor needs to be considered carefully either as a nuisance or as a “free capacitor” that can shape amplifier behaviour with a bit more design freedom. ii) Harmonic distortion quickly becomes a problem as signal magnitudes increase if only Rg is replaced by a memristor, but there may be a class of problems involving very fine input signals where the memristors act in a sufficiently linear region to obviate this problem. Also, applying multiple memristors can improve the signal distortion, as memristors compensate the nonlinear characters of each other. iii) When balanced finely, the RC characteristics of the memristor can provide a slight but possibly important advantage by extending the -3dB cut-off region and sharpening the transition between pass-band and roll-off as shown in Fig 3 27kΩ memristor and 30kΩ resistor. In conclusion, the relatively low-cost reconfigurability bequeathed by memristive trimming unto instrumentation amplifiers seems to come with acceptable losses in other areas such as THD for at least certain application areas, thus removing a roadblock towards the viability of memristively-tuned analogue AC electronics.

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