A Variable Bandwidth Memristor-Based Legendre Optimum Low-Pass Filter for Radio Frequency (RF) Applications

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Abstract

This paper presents the enhancement of Legendre Optimum low pass filters in terms of reusability and bandwidth, based on the variable or programmable memristance of memristors. Two low pass filters, of third and fifth order, operating in the radio frequency range, and designed using the insertion loss method are presented. At 600 KHz and at 110 MHz, two MS memristor models, of the non-linear ion drift class is incorporated into the filter circuits in turn and their memristances varied such that $R_{off} - R_{on}$ decreases monotonically and $R_{off} - R_{on} > 0$. Results show a bandwidth enhancement of up to 100 KHz at 600 KHz, and up to 19MHz at 110MHz. This study also examines the effect of the simultaneous versus asynchronous variation of the memristance of the pair of memristors introduced into the filter circuits, as well as increase in filter order.

Index Terms: Legendre optimum low pass filter, memristive filter, memristor, RF filter, variable bandwidth filter.

I. INTRODUCTION

Current trends show a major drift towards wireless last miles. This is encouraged by an ever-growing interconnection of devices, spurred by advances in IoT and Edge Computing. Wireless communications standards set out in the IEEE 802.11xx, as well as in IEEE 802.15, 802.16, 802.20 and 802.23 show frequency allocation for wireless communication under different technologies. The rapid increase in the number of devices seeking to transmit modulated information over the bandwidth of these channels demand a better technique for signal processing (including filtering, separation and noise suppression) at the receiving end of communication devices. A modern mobile telephone for example is designed to utilize WiMAX, GPS, WLAN, receive and transmit signals on GSM, 3G, 4G and 5G networks and support all wireless applications these technologies offer, with excellent performance. It is common knowledge that these services are available on different frequency bands to avoid negative effects such as interference and crosstalk. This means that modern electrical and electronic devices need multiband filters for efficient signal handling and processing. While the consumer devices themselves benefit more from use of band pass filters, low pass filters are indispensable in communication equipment and the likes.

Device scaling comes at the price of high frequency operation. Above VHF, physical components' dimensions become substantial in comparison to the wavelength (λ) of the operating frequency, making it impractical to use lumped elements. In situations where the component dimensions equal or is greater than 0.1λ, distributed elements provide a suitable alternative to lumped elements. Examples of distributed elements include transmission lines, microstrip and DGS (defected ground structure). Taking advantage of the harmonic intervals in distributed elements together with the use of techniques like frequency tuning using loaded stub resonators [1], it is feasible to design multiple passbands. The techniques used in the synthesis of multiband filters include use of stepped impedance resonators (SIR), frequency transformation, coupling matrix and use of loaded stub resonators [1] [2]. A technique of transforming an ultra-wideband-pass filter (UWB BPF) into separate band-pass filters is presented in [3] [4] [5 - 10] provides more discussion on additional techniques for designing multiple passbands in filters and [11] on reconfigurable passbands. In this study, the operating frequencies of the filters presented are low enough that lumped components can still give accurate results.

This work presents a variable bandwidth, passive, lumped element Legendre Optimum (L-Opt) low-pass filter for use in the RF band. This filter has a monotonically decreasing response and the maximum cut-off slope among all filters of a monotonic class [12]. This feature, in addition to its ripple-free pass band makes it desirable. The novelty of the proposed filter lies in the use of Legendre-Optimum low pass filter approximation with MS memristors to achieve a variable bandwidth low pass filter. To the best of the authors' knowledge, no such work has been done. The case for adopting the proposed filter is made stronger by the output response comparison in Figure 1. Notice that for the same order, the L-Opt filter has a steeper roll off than the Butterworth filter and has no ripples in the passband like the Chebyshev filter. Table III shows a comparison of other works found in literature to the proposed filter, all of which used ideal filters instead of a more practical filter approximations.

II BACKGROUND

A. Filters: Types and Classification

A filter is an electrical device which modifies its input signal with reference to frequency [13]. In the general sense, filters separate composite mixtures into individual components or other composite mixtures with similar properties. The output signal has specific characteristics as a result of the input transformation, based on its design and application [14]. Frequency-selective filters are described with regard to their pass-bands [15]. For instance, a low-pass filter passes low frequency components below its cut off frequency, but suppresses high frequency components.

Filters can be classified as passive or active. The former contains only passive components (R, L, C and M) while the latter contains active components like transistors and operational amplifiers in addition to passive components. There are five ideal magnitude characteristics of a filter, namely: low-pass (LPF), high-pass (HPF), band-pass (BPF), band-reject (BRF) and all-pass filters (APF) which cannot be realized by finite networks [16]. Therefore, all real filters have characteristics which approximate those of the aforementioned ideal filters [16]. Proximity of the approximation's performance to the ideal behavior is very desirable. However, the cost of a filter increases with its quality and performance [17]. Butterworth, Chebyshev, Elliptic and Bessel approximations are well-known filter approximations discussed by C. Butterworth in 1930 [18]. Butterworth filter has a smooth transition, whereas the Chebyshev-I filter has a sharper run-off compared to the Butterworth filter [18]. Both the Butterworth and Chebyshev approximations have an all-pole transfer function. A filter combining the desirable features of Chebyshev and Butterworth filters was introduced by A. Papoulis in 1958 as the Legendre filter [12]. It has a sharper roll off than a Butterworth filter, but a smoother phase response than a Chebyshev filter [19]. Transitional filters are developed to combine conflicting properties of two or more different filters [20]. A transition of the characteristics of Butterworth and Chebyshev filters can be achieved via

Pascal filters, Legendre polynomials, optimum L-type and Legendre filters [20]. Figure 1 shows a comparison of the magnitude response of the Butterworth, Chebyshev and Legendre Optimum (L-Opt) low pass filters.

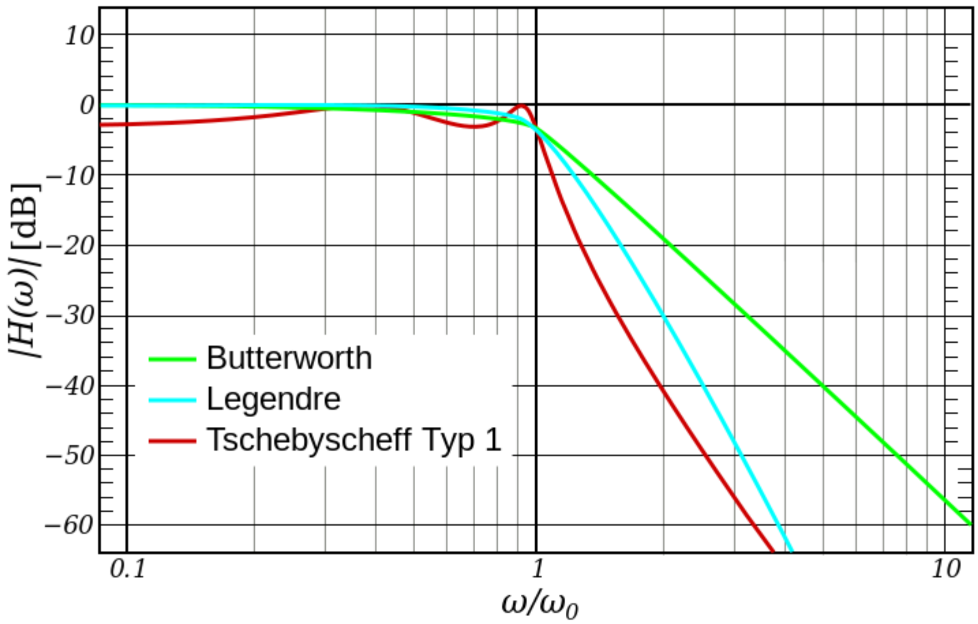

Figure 1: Comparison of the Magnitude Response of Butterworth, Chebyshev and Legendre Filters [21]

B. The Memristor

Characterized by L. Chua in 1971, the memristor is an element that shows a non-linear relationship between electric charge and magnetic flux [22]. Defined by state-dependent Ohm's law, the memristor is a passive, two terminal nanoscale device whose resistance depends on one or more internal state variables of the device [23]. This varying resistance ("resistance switching") depends on the entire waveform of the previously applied voltage or current, how long it was applied and the direction of the energy flow [24] [25]. [25] and [26] detail the descriptive equations of memristor operation. Memristors can be applied to realize memristive analog circuits having adjustable characteristics owing to the programmable resistance of a memristor [27].

Memristance can be accurately controlled in order to optimize the performance of microwave circuits [28] as well as to design reconfigurable RF/microwave planar filters [29]. It should be taken into account that reconfigurable band-pass filters consume low energy compared to traditional RF/microwave switches [29]. Figure 2 shows the characteristic hysteresis loop of a memristor. It passes through the origin. As frequency increases, the hysteresis loop shrinks to a straight line as the difference between R_{on} and R_{off} gets smaller, till the device's I-V characteristic becomes a straight line (linear resistance). Mathematical models used to study the memristor include: the linear ion-drift model (HP's model), non-linear ion-drift models (Strukov, Benderli & Wey [30], Jogglekar, Biolek [31], Prodromakis, Lehtonen and Laiho [32] Models [33]), Simmons tunnel barrier model (Abdalla and Pickett model [34]), threshold adaptive memristor model (TEAM) and the voltage threshold adaptive model (VTEAM). Researchers have long experimented with filters. From the time the memristor came on the scene, efforts have been made to study its effect on filter circuits, in a bid to improve filter performance. Low-pass filters find application in handling radio signal interference, cross talk prevention, noise cancellation and audio amplification in signal processing.

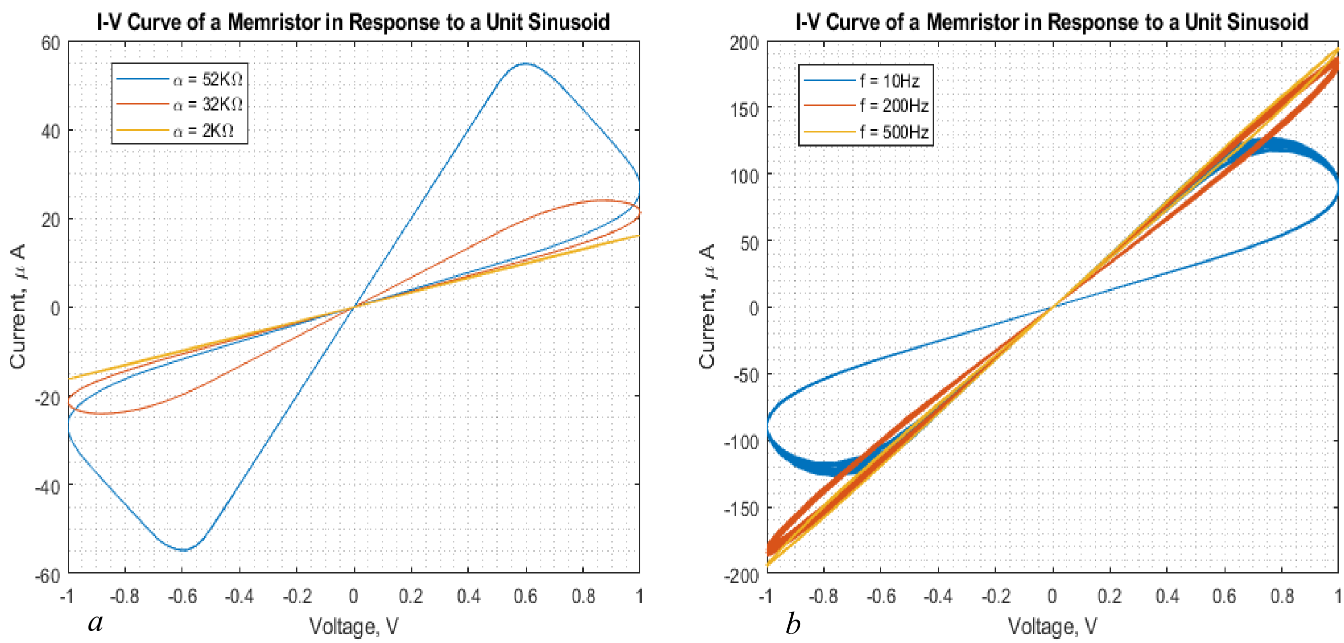

Figure 2: Behavior of the Hysteresis Loop of a MS Memristor (a) With Decreasing $\alpha = R_{off} - R_{on}$ at Constant Frequency (b) With Increasing Frequency at Constant R_{init}.

The Legendre low pass filter is important because it combines the good features of the Chebyshev and Butterworth filters and hence has practical applications from a design perspective. The following are some of the example of research into the use of memristors in filter circuits. Kumar et al detail the design of Legendre group of low-pass filters [20]. Their work showed the design process for a variety of Legendre low pas filters. With regard to studying the effects of memristive components on filter circuits, Chenyu et al demonstrated the incorporation of memristive components into a high-pass filter to show time-variance of filter characteristics as a result of the programmability of the components [35]. Yifan et al published a similar work on the modification of a single pole ideal RC low-pass filter with a memristor (RC LPF to Mem-C LPF), then memcapacitor (Memristor-Memcapacitor LPF) to show a time-variance of the resulting filters' transfer function and cut-off frequency [36]. [37] details experimentation with modified RLC series circuits and in demonstrating the signal division (filtering) model, the authors replaced the resistor and capacitor in a typical double-pole, passive, RLC series circuit with a memristor and memcapacitor respectively [37]. The study used the non-linear dopant drift model of the memristor [22] and the piecewise linear model of the memcapacitor [38]. It reports improvements in time-variability and controllability of the resulting band-pass and band stop filters. Vishnu et al reported the effects of incorporating a Voltage Threshold Adaptive Memristor (VTEAM) into active, single-pole low-pass, high-pass and band-pass filters [39]. The focus of their work was on the effect of memristors on the cut-off frequency and gain of active single-pole filters. Xu et al examined the potential applications of memristors to microwave devices by loading a microstrip transmission line with a memristor. Their design also featured a reconfigurable microstrip band-pass filter with a resonator loaded by a memristor and a microstrip patch antenna earthed with the help of a memristor acting as a carrier-wave modulator. Xu et al also developed mathematical abstractions (integrators) of the memristor and compared experimental results obtained with the integrators with that of known SPICE memristor models [40]. Anjali et al examined the impact of memristor, meminductor and memcapacitor on the power consumption of low-pass, band-pass and high-pass filters [41]. Although [41] showed the used of memristors with a low-pass filter, its work is limited to single pole filters and focused on power needs.

To the best of the authors' knowledge, ideal filters are unsuitable for studying real filters' performance, as was the case with almost all the studies above. Hence the current study uses the Legendre low-pass filter (a combination of the Chebyshev and Butterworth approximations). Here we also use multiple poles, as would be expected in real filter systems with multiple filtering stages. Additionally, unlike in any of the reviewed works, this study examines the effect of the MS memristor model on the L-Opt low-pass filters of third and fifth order. SPICE model of memristor with non-linear dopant drift is utilized in this work to construct a memristive L-opt low-pass filter to check its viability for reuse in RF/microwave applications.

The remaining sections of this paper are organized as follows: Section III discusses the proposed filter schematics and the design considerations. It also lays out the plan for demonstrating that the very practical L-Opt LPF is configurable and can be reused. Section IV presents the results of the experimentation in the previous section and explains the implications of the observations. Section V draws conclusions on the viability of the proposed filter for reconfigurable use based on the results in Section IV.

III PROPOSED MEMRISTOR-BASED LEGENDRE OPTIMUM LOW-PASS FILTER

Filter designers usually determine: type of filter, per design requirements (LP, HP, BP, BS and the appropriate approximations), stop and pass band attenuation, filter bandwidth and cut-off frequency, number of filter elements, sensitivity and topology [20] [42 - 46]. Since ideal filter performance cannot be implemented using a finite network, approximations of ideal filters are used instead. The amplitude response of these category of filters are estimated using an approximating function F(n, ω). The generic gain (G) expression reads:

$$G(n,\omega) = \frac{H_0}{\sqrt{1 + \varepsilon^2 F^2(n,\omega)}} \quad (1)$$

For the more popular Type-1 Chebyshev filter (due to its faster roll-off) the amplitude-response is equal to the transfer function of the filter. That is:

$$G(n,\omega) = H(n,j\omega) = \frac{1}{\sqrt{1 + \varepsilon^2 F^2(\frac{\omega}{\omega_0})}} \quad (2)$$

For Butterworth filter:

$$G(n,\omega) = \frac{1}{\sqrt{1 + (\frac{\omega}{\omega_0})^{2n}}} \quad (3)$$

With the Type-II Chebyshev filter, the gain formula has the second term in the denominator of Equation (3) above inverted. Using the gain function, one can calculate the poles of the filter as the zeros of the denominator.

For the three major filter approximations, the function $F(n,\omega)$ is defined as follows:

$$F(n,\omega) = \begin{cases} \omega^n, & Butterworth\ Filter \\ C(n,\omega), & Chebysev\ Filter \\ R(n,\omega_s,\omega), & Elliptic\ (Cauer)\ Filter \end{cases} \quad (4)$$

$$Ripple\ factor, \varepsilon = \sqrt{10^{\delta/10} - 1} \quad (5)$$

$$\text{Filter Selectivity}, F_s = \frac{n}{2\sqrt{2\omega_0)}} \qquad (6)$$

$$\text{Attenuation}, A = 10\log\left(1 + \left(\frac{\omega}{\omega_0}\right)^{2n}\right) \qquad (7)$$

where: $H_0 = 1$

n is the order of the polynomial describing the approximation.

$C(n, \omega)$ refers to the Chebyshev polynomial of order n

$R(n, \omega_s, \omega)$ is the Elliptic rational function of order n. δ is the passband ripple in decibels

ω, ω_0 are the angular frequency and cut-off frequency respectively

A properly designed filter is expected to achieve the stop band attenuation at the upper limit of passband frequency (also known as the stop frequency or cut-off frequency). Attenuation in the passband is set by the designer, usually at 3dB or less. The stopband attenuation is also specified during design, usually around 20dB and above, depending on application. The passband frequency describes the bandwidth of the filter, it has a lower and upper limit except in the case of a low-pass and high-pass filters where the lower band corresponds to zero and the cut-off frequency respectively. A number of topologies are used in the implementation of filters. However, the Cauer topology is commonly used for realizing passive filter implementations. The analysis on transfer functions is made in Section III.

Both the Butterworth and Chebyshev approximations have an all-pole transfer function. The Butterworth approximation has the smoothest transition from passband to the stopband as well as a very smooth linear phase transition, making it the approximation of choice when designing a low phase distorting and moderate selectivity filter. The Chebyshev filter allows ripples in the passband and a steeper transition characteristic in addition to a less linear phase transition in comparison to the Butterworth filter. The inverse Chebyshev filter (Type-II) is the opposite of the Chebyshev filter (Type-I). The Elliptic approximation allows ripples in the passband and stop band. This enables it to provide the best selectivity characteristic of any of the approximation methods. It is however, the most challenging to design and has the worst phase distortion of the filter approximations.

A. Papoulis recommended an LC ladder realization of his hybrid transitional filter [12]. The Legendre filter borrowed from its parent filters, the desirable features of high attenuation rate in the stopband and no ripples in the passband. Additionally, for a given order of filters and under the condition of a monotonically decreasing response, the L filter has the maximum cut off rate, which is expected given the nature of the Legendre polynomial [44]. Investigations by Chryssomallis et al involving simulations of the Legendre filter and subsequent observations from the attenuation, group delay and phase response plot revealed that the L filter has more in common with the Chebyshev filter given that it has a sharp cutoff and ripples in the passband as well as stopbands [47].

The requirement that RF filters have high selectivity, small group delay variations and low loss in the passband cannot be provided by any single approximation. A combination of the Chebyshev, and Butterworth filters yield a hybrid, translational filter called the Legendre low-pass filter. It has no ripples in the passband, has the highest attenuation slope for a given filter order as well as high selectivity [20].

In this work, we used a modified passive, low-pass, LC ladder Legendre-Optimum filters, to demonstrate the features that make this filter type suitable for RF applications with emphasis on reuse and savings in power, resources and space. Following the guidelines in the preceding paragraphs (Equations 1 – 7) and adopting the insertion loss filter design methodology, this work presents the design of a three-pole and five-pole L-Opt low pass filters with KHz and low MHz cutoff frequencies, see Figures 3 & 4, Tables I & II. In addition to filter response to changing memristance, we also studied the effect of increasing the number of poles. For simplicity, we assume a purely resistive load and source impedance. This impedance is then replaced with memristors and used in any of these scenarios:

a. Operating in the linear/sub-threshold region
b. Energized with a high frequency input signal above the threshold frequency
c. Incrementally reducing the magnitude of $R_{off} - R_{on}$ at constant frequency or
d. Using a memristance tuning circuit with scenarios (a), (b) or (c) [48].

Any of the three scenarios yields a linear IV curve upon experimentation. The MS memristor models is used [49]. The impact of the changing memristance on the cutoff frequency, bandwidth and other filter characteristics are captured and presented in the next section.

Tables I & II provide the g- and component values for L-Opt filters of third and fifth order based on Equations (8) and (9). We set $R_s = R_L = 50\Omega$ for $f_c = 600kHz \; and \; f_c = 110MHz.$

Note that:

$$C_n = g_n\left(\frac{1}{R_s\omega_c}\right) \tag{8}$$

$$L_n = g_n\left(\frac{R_s}{\omega_c}\right) \tag{9}$$

We first run AC analysis on the circuits in Figure 3. Then we vary the memristance of the connected memristors using scenario (a) above to 'set' different memristance values in the memristors of Figure 4. Scenario (b) works just the same. In the case of scenario (c), the memristance is tuned using a different circuit and subsequently connected to the filter circuit and to observe the effect(s), if any, on the filter output response characteristics by repeating the AC analysis. Using the filter transformation techniques, which rely on the symmetry of a LPF in addition to numerical and algebraic manipulations in the frequency domain, one can obtain a high pass and band pass filter from the designed low pass filter in Tables I and II [50 – 52].

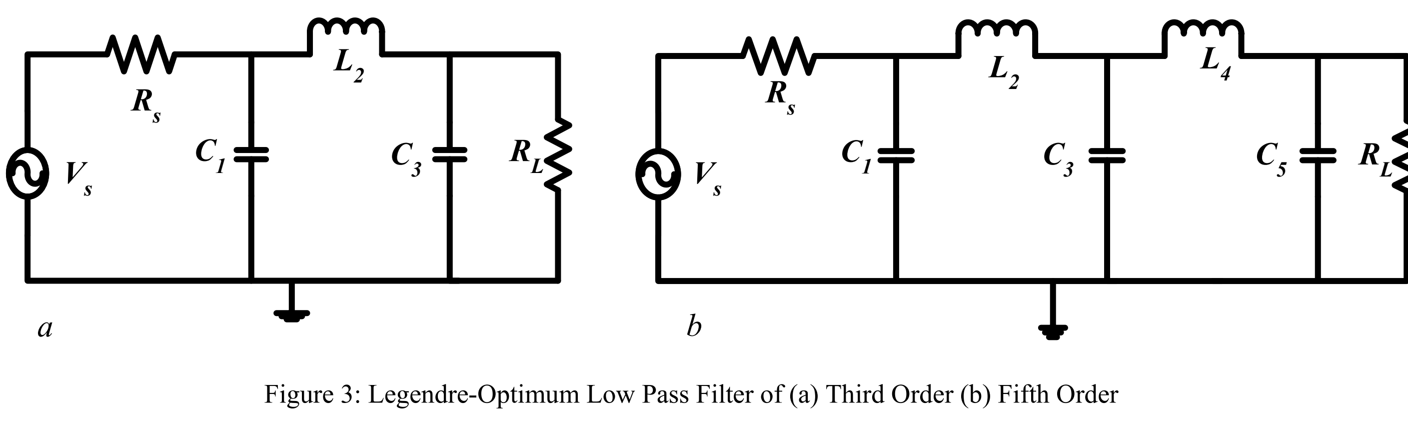

Figure 3: Legendre-Optimum Low Pass Filter of (a) Third Order (b) Fifth Order

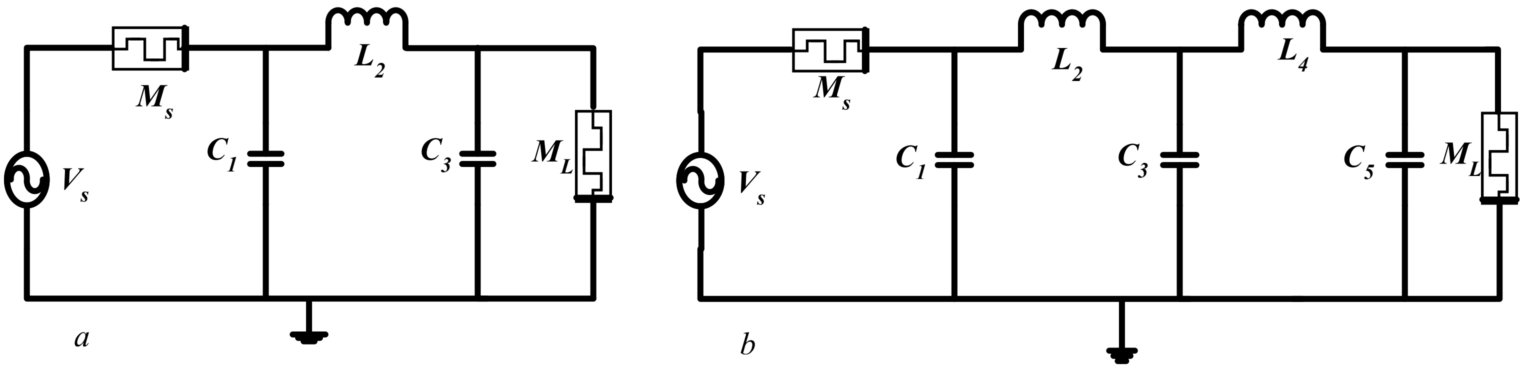

Figure 4: Memristor-Based Legendre-Optimum Low Pass Filter of (a) Third Order (b) Fifth Order

Table I: Calculated Component Values for Fifth order L_Opt LPF

Component Values for 5th Order L-Opt Filters			
g-Value	**Label**	**600KHz**	**110MHz**
1.9990	C1	10.6053nF	57.8465pF
1.5395	L2	20.4184µH	111.3733nH
2.0673	C3	10.9672nF	59.8209pF
1.4780	L4	19.6025µH	106.9226nH
0.9512	C5	5.0463nF	27.5251pF

Table II: Calculated Component Values for Third order L_Opt LPF

Component Values for 3rd Order L-Opt Filters			
g-Value	**Label**	**600KHz**	**110MHz**
2.1801	C1	11.5659nF	63.0865pF
1.3538	L2	17.9554µH	97.9387nH
1.1737	C3	6.2266nF	33.9635pF

IV RESULTS AND DISCUSSION

AC analysis of the filters in Figures 3 & 4 is presented. The operating frequencies of the filters were so chosen that lumped components would still behave typically. A test of the memristor models using a unit amplitude sinusoid yields the signature pinched hysteresis loops shown in Figures 2 (a) and (b), at increasing initial resistance and frequency respectively. This is one of the important features of a memristor. The loop usually passes through zero and as frequency increases, the hysteresis loop narrows as the difference between Ron and Roff gets smaller [41]. At very high frequencies, the hysteresis loops becomes just a straight line and the device acts like a linear resistor [53]. Although the proposed circuit would be simpler in terms of cost and complexity if one just uses a variable resistor instead of a memristor for high frequency applications, there is an argument to be made about power consumption, dimension and programmability, in favor of the memristor.

The plots of Figures 5 - 8 show in:

- 5 – 8 (a), the amplitude and phase response of the third and fifth order L-Opt LPFs at 600KHz and 100MHz, as designed
- 5 – 8 (b), the magnitude response of the third and fifth order L-Opt LPFs at 600KHz and 110MHz with R_S *and* R_L varied simultaneously using a memristor (constant f, changing α, as in Figure 2a)
- 5 – 8 (c), the response of the designed filter when R_S is constant and varying R_L

The results show that at either 600 KHz or 110 MHz, simultaneous variations in R_S and R_L ($R_S, R_L < R_{off}$) introduces ripples in the passband and significantly reduces the cutoff frequency and bandwidth of the filter, with corresponding changes in phase, see Figures 5 - 8 (b). The biggest reduction in cutoff frequency in the KHz range occurred in Figure 5(b) i.e. from 600 KHz to 301Hz, and from 110 MHz to 36 KHz in the MHz range (Figure 8b). On the other hand, variations in R_L alone, causes very minimal passband ripples and significantly increases the bandwidth and obtainable cutoff frequency at $R_S, R_L < R_{off}$, for each memristor type. In the KHz range, the biggest enhancement is seen in Figure 6(c) i.e. 600 KHz to 700 KHz while in the MHz range 110 MHz to 130 MHz cutoff bandwidth enhancement is seen in Figure 8(c). This shows that the cutoff frequency (and therefore bandwidth, for a LPF) can varied. And a single filter circuit can be reused and reconfigured for operation at a different frequency. Depending on application, the ripples in the passbands of Figures 5 – 8(b) may not always be a problem.

For the same filter type (L-Opt LPF in this case), an increase in the number of poles (from 3 to 5) slightly made the roll-off steeper. These results confirm that a memristor-based low pass filter is a viable technique for designing an adjustable or programmable LPF. Table III shows a comparison of the current work with similar works found in literature.

The technique of varying (reducing) $\alpha = R_{off} - R_{on}$ at constant frequency is used in this study to obtain different memristance values for the memristors incorporated into the filter circuits. Other techniques for achieving the same outcome have been described in Section III. As α decreases, the I-V curve becomes steeper and Δx becomes smaller, implying increasing conductance as the once non-linear memristor tends to a linear resistor. This change in conductance with decreasing α us responsible for the varying memristance recorded.

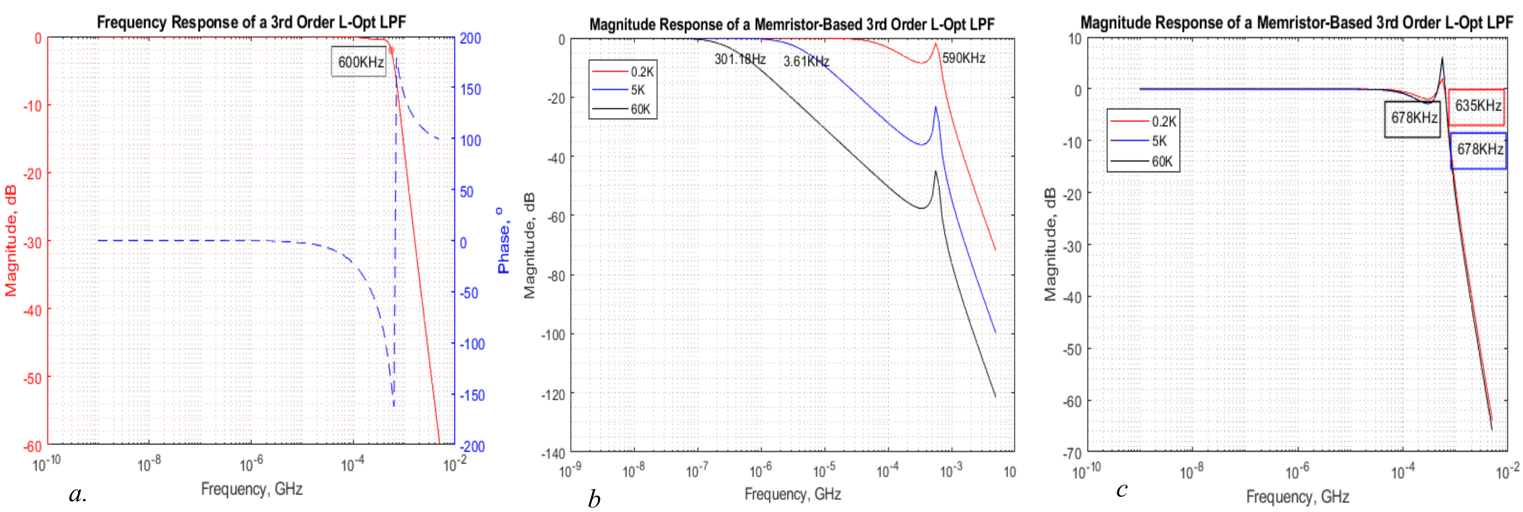

Figure 5: Output Characteristics of a **3rd Order** L-Opt LPF $f_c =$ **600KHz** (a) $R_S = R_L = 50\Omega$ (b) R_S *and* R_L varied simultaneously using a memristor (c) $R_S = constant$ while R_L varies. **MS memristor model.**

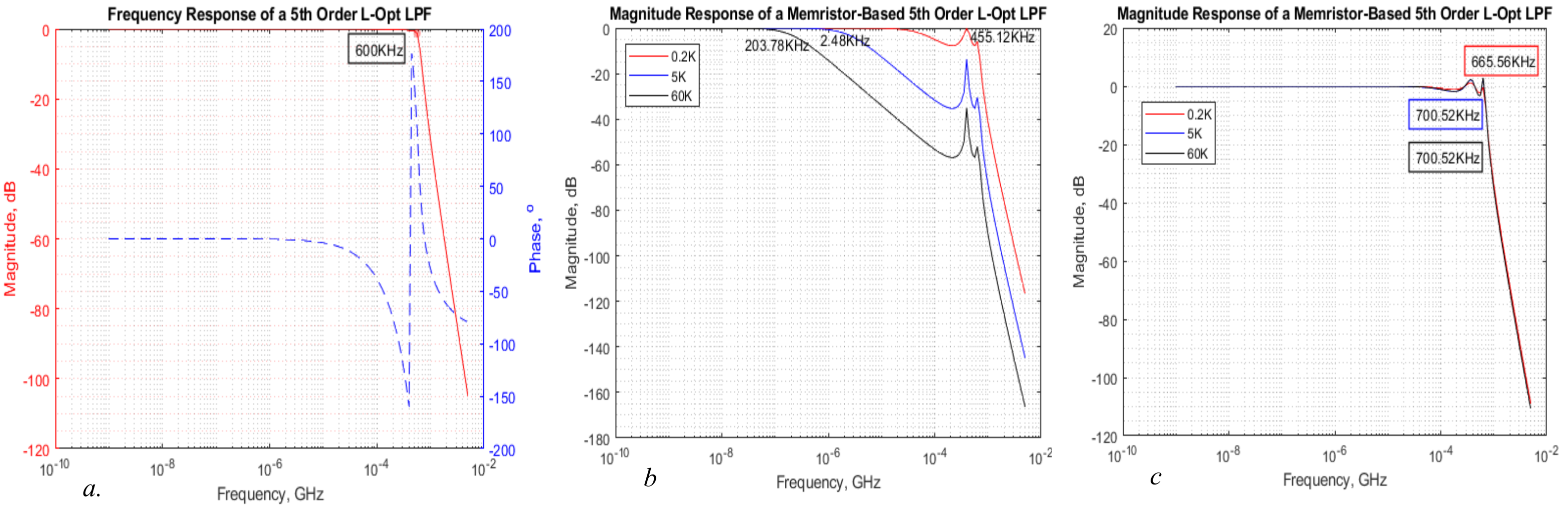

Figure 6: Output Characteristics of a **5th Order** L-Opt LPF $\boldsymbol{f_c =}$ **600KHz** (a) $R_S = R_L = 50\Omega$ (b) R_S *and* R_L varied simultaneously using a memristor (c) $R_S = constant$ while R_L varies. **MS memristor model**

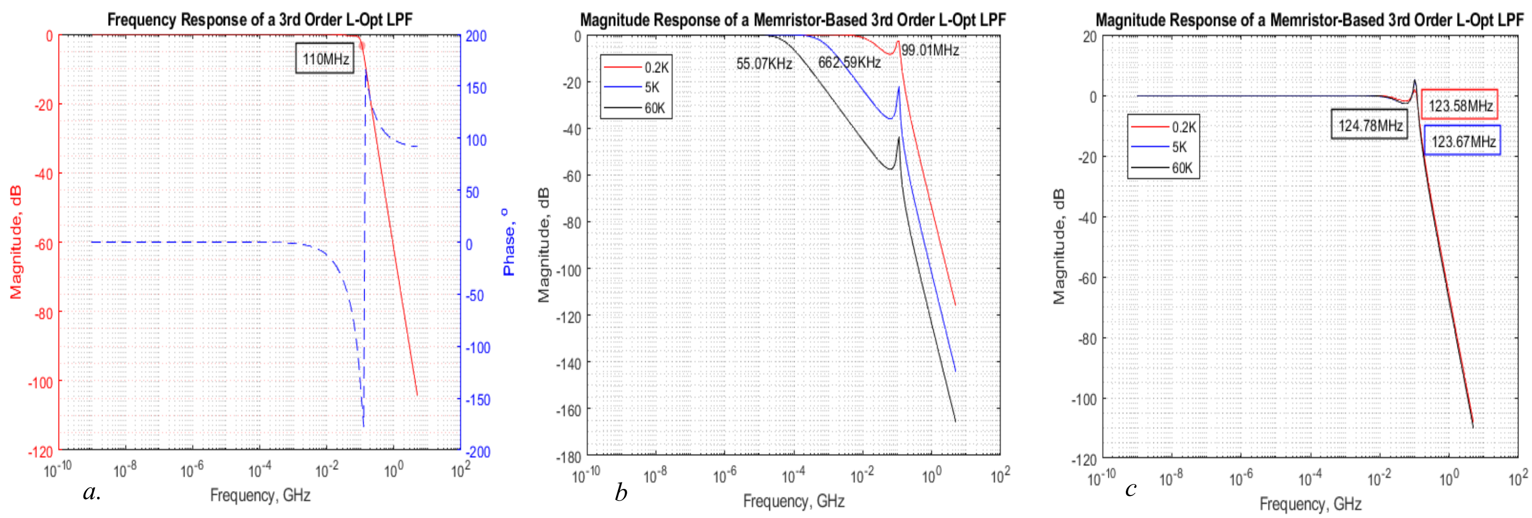

Figure 7: Output Characteristics of a **3rd Order** L-Opt LPF $\boldsymbol{f_c =}$ **110MHz** (a) $R_S = R_L = 50\Omega$ (b) R_S *and* R_L varied simultaneously using a memristor (c) $R_S = constant$ while R_L varies. **MS memristor model**

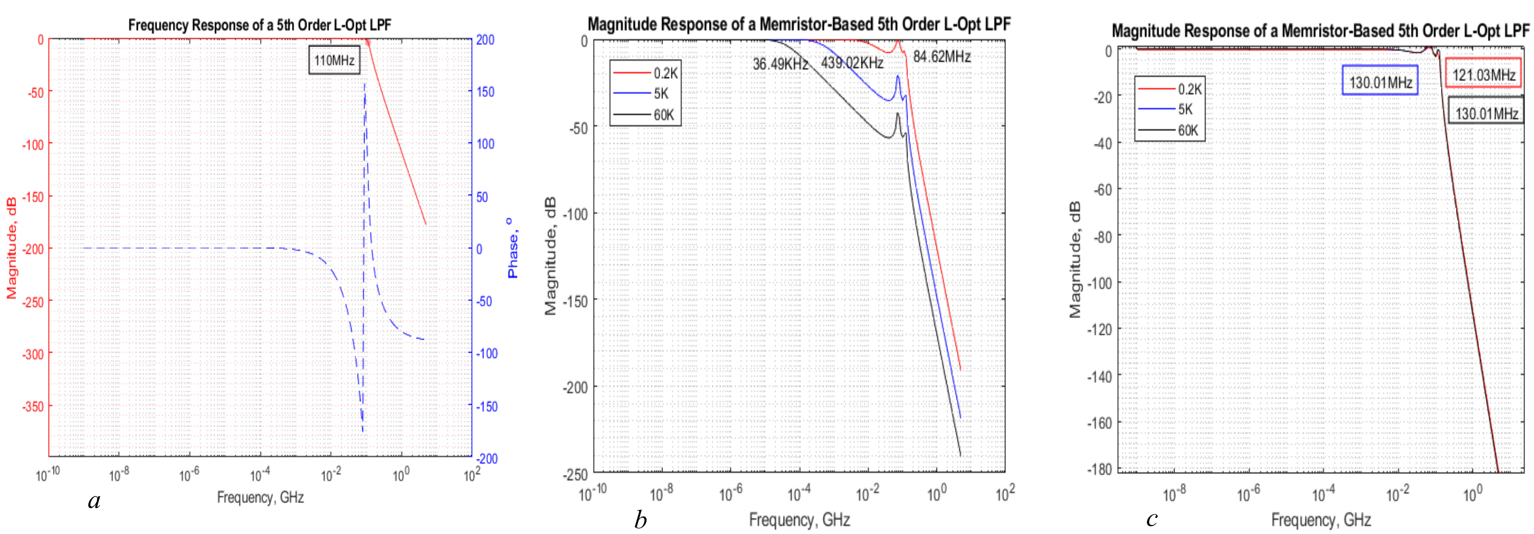

Figure 8: Output Characteristics of a **5th Order** L-Opt LPF $\boldsymbol{f_c =}$ **110MHz** (a) $R_S = R_L = 50\Omega$ (b) R_S *and* R_L varied simultaneously using a memristor (c) $R_S = constant$ while R_L varies. **MS memristor model**

Table III: Comparison of Proposed Filter Circuits with Other Works

Feature	[24]	[25]	[26]	[28]	[30]	Proposed Design
Filter Type by Function	HPF	LPF	BPF, BSF	HPF, LPF, BPF	HPF, LPF, BPF	**LPF**
Experimental Configuration	RC	RC	RLC	Active filters	RC, RL, LC	**LC**
Filter Type by Component	Mem-C	Mem-C	Mem-L-Memcap	Mem-C-X	Multiple	**Mem-L-C**
	Mem-Memcap	Mem-Memcap	-	-	-	**-**
Filter Order	1	1	2	1 - 2	1 - 2	**3, 5**
Used ideal filter	Yes	Yes	Yes	Yes	Yes	**No**
Filter Approximation Used	-	-	-	-	-	**Chebyshev + Butterworth**
Memristor Model Used	Jogglekar	Jogglekar	Jogglekar	VTEAM	-	**MS**
Memcapacitor Model Used	PLM	PLM	PLM	-	-	**-**
Max Bandwidth Achieved	-	-	10 KHz	28 KHz	-	**700KHz at 600KHz, 130MHz at 110MHz**
Variable Filter Realized	Yes	Yes	Yes	Yes	Yes	**Yes**

V. CONCLUSION

In this paper we have presented a memristor-based, adjustable bandwidth low pass filter using the variable memristance of a memristor. It demonstrates the potential for filter reuse or reconfiguration. Depending on application, either configurations (b) or (c) show potential. An increase in f_c of up to 100 KHz was recorded at 600 KHz, and up to 19 MHz at 110 MHz We conclude that the bandwidth and cutoff frequency of a LPF (and other filter types by extension) can be adjusted using the variable memristance property of a memristor in order to save power, resources and space in modern filter design in a programmable filter.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest and have not received any funding towards the completion of this study.

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