An Envelope Detector Based on Memristive Systems

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***Abstract*—The Bipolar Memristive Systems with Threshold (BMST) are promising building blocks for analog signal processing. The present work describes their use in designing an envelope detector that can, in particular, be applied in automatic amplitude stabilizers or in the field of computing units, classifiers, as well as in a number of various types of low-voltage and low-power nonlinear systems for signal processing. The operation of the proposed circuit has been verified via PSpice simulations.**

***Index Terms*—Envelope Detector; Memristive System; Threshold Voltage.**

I. INTRODUCTION

The area of the applications of general memristive systems has been steadily expanding. The number of articles on their applications for analog signal processing has also been increasing exponentially. Articles from the field of memristive systems are available in the online database [1], where one can follow the development on a daily basis.

Despite the often-unwise innovations of existing circuit solutions [2-4], where disadvantages such as nonlinear distortion, offset, etc. of inappropriately selected types of memristive system are not taken into account [3], [4], interesting designs of circuits utilizing the unique properties of memristive systems have been emerging on an increasing scale. Some examples are given in [5-9]. In [10], important aspects in selecting appropriate memristive systems for a proper functioning of analog applications are mentioned. There are different classes of memristive systems for linear and nonlinear applications. Similarly, it is necessary to distinguish between inertial and non-inertial applications

Thus, in relation to [10], requirements for memristive systems for monitoring the envelopes of general analog signals can be specified. The Bipolar Memristive System with Threshold (BMST) [11-13] might be a suitable type for this application. Such a BMST is, in terms of its behavior, similar to the low-voltage diode. This article features a design of a simple BMST-based envelope detector and the verification of its function via PSpice simulations. Further, the article features a modified envelope detector that enables, compared to the classical circuit with diodes and a capacitor, adjusting its parameters in dependence on the level of the modulated signal.

II. MEMRISTIVE SYSTEMS FOR NONLINEAR APPLICATIONS

A specific behavior of an ideal voltage-controlled memristor is described by the following port and state equations [14]:

$$i = g(x)v \ , \tag{1}$$

$$\frac{d}{dt}x = v \ . \tag{2}$$

Here, i and v stand for the memristor current and voltage, x is the state variable, and g is a nonlinear function modeling the memductance as a function of the memristor state. The state variable x is actually the integral of the voltage on the memristor, i.e. the flux, as clear from the differential equation (2). An ideal memristor is not suitable for designing real circuits, mainly because of its infinite depth of memory [15] and the ability to continuously integrate, thereby amplifying the offset. Considering the threshold property in the state equation might be a solution to this problem. The corresponding component, with its operation similar to that of a low-voltage diode, is the above Bipolar Memristive System with Threshold (BMST) [11-13].

The simplest BMST model can be described by the following modified port and state equations:

$$i = R_M^{-1} v \, , \tag{3}$$

$$\frac{d}{dt}R_M = f_L(v) \ . \tag{4}$$

The relationship between the voltage and current is given by state-dependent Ohm's law (3). Here the memristance R_M serves as a state variable, whose derivative with respect to time depends, according to (4), on the nonlinear function f_L. This function is dependent on the terminal voltage such that it introduces the threshold voltage into the element behavior, see Figure 1(a). The limit values of the threshold voltages V_{t-} and V_{t+} also have a major impact on the nonlinear behavior of this memristive system, providing immunity to offset and drift. For a low-voltage signal, these levels should be as low as possible but concurrently preserving the above immunity.

The behavior of the $f_L(v)$ function outside the threshold region is defined by its slope β [$A^{-1}s^{-1}$]. Equation (4) indicates that the parameter β controls the time derivative of the memristance depending on the voltage, thus determining the dynamic behavior of the system.

It is likely that the technological progress enables will in the near future enable producing such BMSTs that would provide the possibility of setting various slopes for the negative and positive polarities of the terminal voltage. In comparison with Figure 1(a), the corresponding function $f_L(v)$ in Figure 1(b) is asymmetric. The corresponding BMST can be advantageously used in the modified envelope detector.

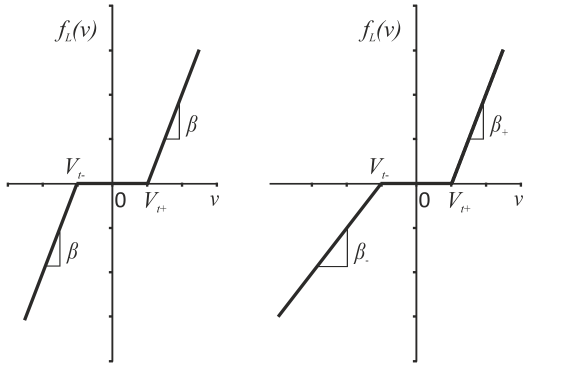

Figure 1: Example of graph of (a) symmetric [11] and (b) non-symmetric function f_L.

For relatively high values of the β slope (hundreds of $GA^{-1}s^{-1}$), the system operates in the bistable mode with two limit states, ON and OFF. In the ON (OFF) state, the memristance R_M is low (high), denoted R_{on} (R_{off}). The limit conditions can be introduced via modifying the state equation (4) by the window function $w(R_M, v)$:

$$\frac{d}{dt}R_M = f_L(v)w(R_M, v) \cdot \qquad (5)$$

The window function takes two values (1 and 0) as shown in Figure 2. It can be expressed via unit step $\Theta(\,)$ functions as follows:

$$w(R_M, v) = \\ \theta(v)\theta(R_{off} - R_M) + \theta(-v)\theta(R_M - R_{on}) \qquad (6)$$

According to the polarity of the BMST voltage and the latest state, the window function switches between two values. For a positive voltage, the function is positive (=1 in a simple case) when the memristance is less than R_{off}. Then, according to Equation (5), the derivative of R_M with respect to time is positive and thus the memristance increases towards its upper limit, R_{off}. Here the window function changes towards zero, which stops the evolution of the memristance R_M. If the terminal voltage changes its polarity, the window function switches to a nonzero value. Considering the subsequent drop in the terminal voltage below the threshold value (V_{t-}), the memristance starts to decrease towards its lower end R_{on} according to Equation (5). In addition, the window function disables the well-known "stick effect" at the boundaries.

The following PSpice simulations use the above window function, completed by an approximation of the step function with the continuous sigmoidal function. This eliminates the convergence problems during the simulation.

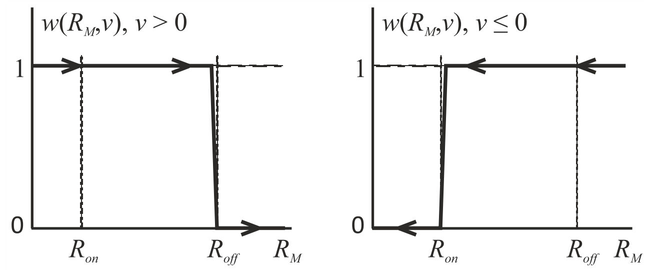

Figure 2: Graph of the Biolek window function *w* [11] [16].

Figure 3 shows the current-voltage (I_M vs. V_M) characteristics of the BMST as a result of DC analysis in PSpice. For the BMST modeling, the following parameters have been used: R_{on} = 100 Ω, R_{off} = 100 kΩ, $\beta = 10^{14}$ (10^{10}) $A^{-1} \cdot s^{-1}$, $V_t = 10^{-4}$ (10^{-1}) V.

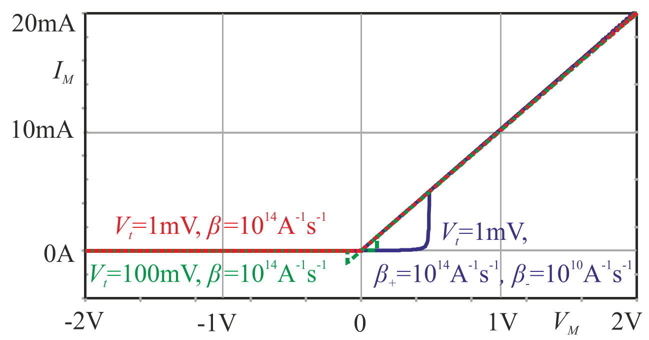

Figure 3: Current-voltage characteristic of the BMST element with various threshold voltages and slopes.

The typical "butterfly" characteristics about the *i*-*v* origin are caused by a non-zero threshold voltage. By lowering the threshold voltage, this effect is virtually eliminated. The reduced slope of β_- becomes apparent with the step change of the memristance being smoothed by exponential course until the ON state is attained. By changing the polarity, this exponential smoothing is not applied because a higher slope β_+ applies to this direction. After the state of the memristive system switches to its limit value, the system behaves as a linear resistor. We can speak of a bistable linear resistor that switches between two states depending on the terminal voltage. Assuming $R_{off} \gg R_{on}$, it can be therefore used as a diode.

The critical parameters of the memristive system used in the envelope detector include the threshold voltage, the ON-state memristance, the R_{on}/R_{off} ratio, the negative β_- slope, and the change-over time between individual states, affecting the dynamics of the detector.

Figure 3 indicates that the processed voltage waveforms must have higher amplitudes than the thresholds of the BMST.

The following Section describes a design of the envelope detector. The BMST parameters are selected with regard to the optimum operation of the detector.

III. Memristive Envelope Detector

The detector operates on the principle of the MAX circuit, which was described for the first time in the publication [6] and then applied in [10], [14] and [17]. The proposed envelope detector in Figure 4 uses two BMSTs working in two limit states (ON and OFF). The BMSTs are modeled by Equations (3), (5) and (6). The key parameters, i.e. the threshold voltage V_t and the slope β, must be designed carefully. In addition to the pair of memristive systems, two capacitors accumulating the charges that correspond to the positive and negative amplitudes of the processed signal are used in this circuit idea.

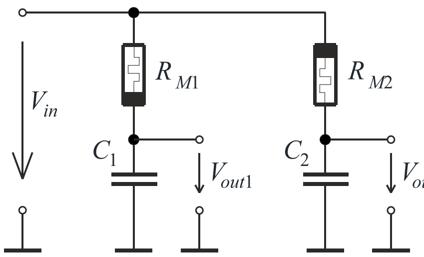

Figure 4: Memristive envelope detector.

If the parameter β is selected sufficiently high for both BMSTs, then the memristive systems change their memristances discontinuously between the limit states R_{on} and R_{off}, depending on the polarity of the terminal voltages. Thus, only with a lower (higher) voltage on the capacitor C_1 (C_2), R_{M1} (R_{M2}) switches into the ON state, and the capacitor is charged to the input voltage. If the input voltage drops (rises), R_{M1} (R_{M2}) switches to the OFF state, thus preventing a decrease (increase) of the output voltage. If the signal is increasing during its detection, the circuit responds immediately and the output signal increases (decreases) within the subsequent period. On the contrary, if the amplitude decreases, i.e. in the extreme case when the input signal turns to 0 V, the capacitor starts to discharge through the OFF-state BMST. Depending on the type of the processed signal, it is necessary to choose a compromise setting of the BMST parameters and the capacitances. The charging / discharging processes are determined by the capacitances, the ON/OFF state memristances of the BMSTs, and the differences between the input and the output voltages.

Low values of the threshold voltage and of the ON-state memristance and, contrariwise, high slope β and high OFF-state memristance will provide rapid responses of the detector to rapid increases of the processed signal. However, such a detector will not be able to follow well the signal during its fast decrease. The output of the PSpice transient analysis of the proposed circuit with the modulated sinusoidal 10 kHz carrier, whose amplitude is switched between 3 V and 1 V, is shown in Figure 5. The parameters of both BMSTs are set as follows: R_{on} = 10 Ω, R_{off} = 10 MΩ, $\beta = 10^{14}$ A^{-1} s^{-1}, V_t = 1 mV.

Figure 5 confirms considerable inertia of the circuit given by the capacitance and by the R_{off} memristance. Reducing R_{off} can partially eliminate this problem, but there will also be slight changes in the output voltage between the two periods of the same amplitude, as is obvious from Figure 6. The parameters of both BMSTs are the same as in the previous case, excepting R_{off} = 100 kΩ.

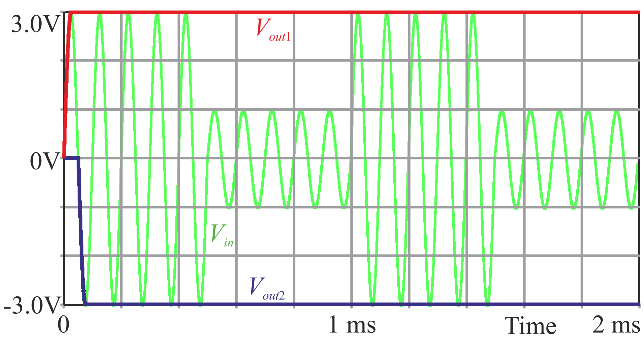

Figure 5: Transient analysis of the envelope detector working as a peak detector.

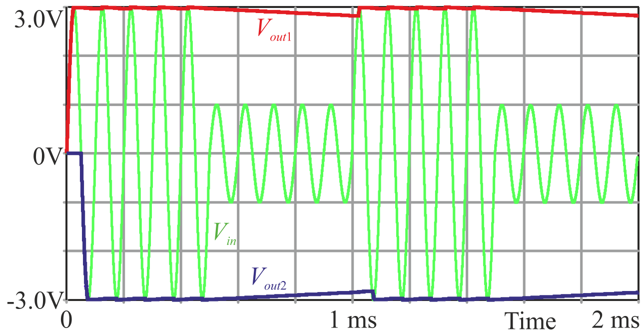

Figure 6: Transient analysis of the envelope detector with lower R_{off} = 100 kΩ.

A drawback of the circuit in Figure 4 is, therefore, the necessity of estimating the waveform of the input signal and then accommodating the parameters of the detector for its proper operation. Such a circuit idea is therefore worthless for practical utilization.

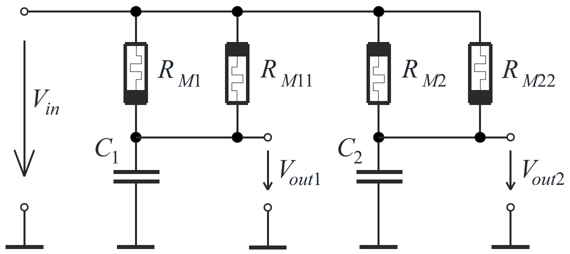

Figure 7: Modified memristive envelope detector.

An interesting solution may consist in complementing both BMSTs with other BMSTs with anti-parallel connection (R_{M11} and R_{M22}) as illustrated in Figure 7. The two original BMSTs operate according to the above principle irrespective of the amplitude drop, i.e. their OFF-state memristances are high. The completed BMSTs have the same parameters except the slope β. The slopes can be set separately for positive and negative polarities of the BMST voltage.

A suitable setting of the negative slope β_{-} of the auxiliary BMSTs can achieve the desired responses to decreased amplitudes of the modulated signal. Important for these auxiliary BMSTs is the moment of transition from OFF to ON state, when the capacitor is being quickly discharged. For R_{M1} and R_{M2}, this transition is instantaneous if the terminal voltage is higher than the threshold value.

However, for R_{M11} and R_{M22} the transition must come after a certain time, for example after 1.5 times the period of the carrier. This property can be affected by a low value of β. By setting the slope at $\beta = 8^9$ A^{-1} s^{-1}, the desired delay occurs as shown in Figure 8.

The advantage of the BMST compared to the ideal memristor consists in its insensitivity to the initial state of memristance. It is obvious from the results of computer simulations that the periodical steady state is established just during the first repetition period.

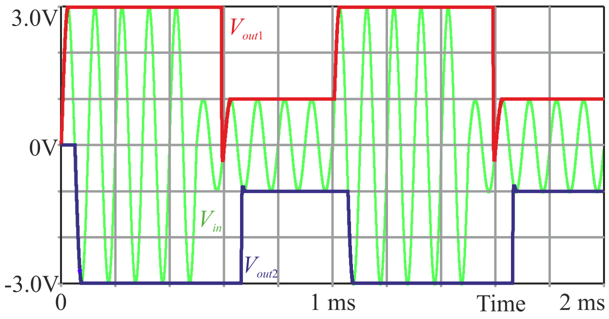

Figure 8: Transient analysis of the modified envelope detector.

IV. Conclusion

The article demonstrates the usefulness of memristive systems of the BMST type for nonlinear analog applications. Such building blocks, produced as nano-devices, would be used in low-voltage and ultra-low-power designs. The optimal performance of the BMST for a concrete application can be set by five parameters, namely R_{on}, R_{off}, U_{t+}, U_{t-}, and β, the last being split into β_+ and β_-.

The envelope detector can be obtained by connecting two or four BMSTs with two capacitors. Compared to the conventional diode-based solutions, the novel circuit enables optimizing independently of one another the accuracy, speed, and response to a reduction of the amplitude. The threshold voltage, R_{on} and R_{off} affect the accuracy whereas the slope β controls the circuit inertia or, for the modified detector, the discharge rate. For the BMST with a fixed slope β, it is obvious that the detector will only be able to process correctly signals from a defined frequency band. A BMST with externally adjustable slope β can eliminate this limitation.

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