A novel RF envelope detector with ultra-wide operation frequency range and enhanced transient response speed

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Abstract: This paper presents an envelope detector that can be used in an ultra-wide operation frequency range (1 GHz\textasciitilde10 GHz) and the transient response time of the detector is less than several nanoseconds. The detector comprises an operational trans-conductance amplifier (OTA), a mirror and a buffer. An extra discharging path is added specially to accelerate the falling-down transient process. The value of the discharging current and the choice of the charging/discharging capacitor are the key factors in the transient process. The circuit is implemented using Huahong 0.18 µm standard CMOS technology. Simulation and measured results are offered showing both better frequency (up to 10 GHz) and transient (several nanoseconds of delay) performance.

Keywords: envelope detector, wideband, high speed, RF

Classification: Integrated circuits

References

1 Introduction

Envelope detectors are very important in a variety of circuits, for instance, the RF power amplifier [1], analog spectral analyzers [2], automatic gain controls [3] and measurement [4]. Especially, they are crucial to the wireless communication transceivers in respect that detectors provide an approach to measuring the signal’s amplitude, which is usually used to be compared with a reference value and then employed in a feedback fashion or in a control loop to optimize power consumption, enlarge input dynamic range, improve linearity of the power amplifier or control the gain of the transceivers. Nowadays, with the development of the wireless communication, the frequency of both carrier and envelope increases. Therefore, a high frequency and wide-band detector has to be realized. Besides, the speed of the transient response is another issue that has to be addressed.

Detectors in the previous works emphasize different characteristic. [5] stresses the fast-setting detector but the operation frequency is low and the time-delay is still at the level of several milliseconds. [6] addresses the bandwidth of the detector, however, the circuit is complex. [7] focuses on the detection accuracy, while the envelope bandwidth that can be handled is low. In this paper, a wideband envelope detector with fast transient response is introduced. The architecture of the detector is shown in Fig. 1.

Fig. 1. Architecture of the detector
The basic structure of the envelope detector discussed here is derived from the work [8] which incorporates an operational trans-conductance amplifier (OTA), a current-mirror used as a rectifying element and a buffer. In this work, an extra current source is added in order to enhance the ability to respond to the input signal. The proposed envelope detector improves the transient response and widens the detection bandwidth.

The organization of this paper is as follows. In section II, the principle of the detector is briefly introduced. The frequency performance and the analysis of the transient response are discussed in section III. The measured results and conclusions are presented in section IV and V, respectively.

2 Principle of operation

The schematic of the proposed detector is shown in Fig. 2.

![Fig. 2. Schematic of the proposed detector](image)

M1~M4 compose the OTA. The current-mirror (M7~M8) is applied as a rectifying element. M11~M13 comprise a source follower, which is used as a buffer. IB1 and IB3 provide the bias currents through (M5~M6) and (M12~M13), respectively. In addition, another mirror (M9~M10) is placed parallel to Cs. It mirrors IB2 to provide a leakage current to discharge the capacitor Cs for the better transient response to input signal.

The OTA transforms input voltage change into current. The current is mirrored through (M7~M8) to charge Cs. Vout is fed back to the input of OTA so that it can closely follow Vin. The buffer is used in order to read out the capacitor Cs without disturbing the stored peak voltage and isolate the detector from the next stage [9].

The input stage, OTA, is the major limitation to the operation frequency range of the detector. On the other hand, the gain of the OTA determines the charging current and sequentially affects the transient response. Therefore, the performance of the OTA is crucial to the whole detector. The capacitor Cs should be small enough for the fast-changing input. However, the ripple of the envelope would become large consequently. As a result, both aspects should be taken into account when it comes to the choice of Cs. The current source IB2, which is mirrored by
(M9~M10), provides the extra discharging current, is another key factor to the transient response performance of the detector. All of these problems will be discussed in the next section.

3 Transient response and frequency performance

3.1 Step response

Step response can characterize the capacity of the detector to follow the fast-changing input signal. The delay time, both rise-delay and fall-delay, is used to evaluate the transient response. Different from the PDSH (peak detect sample and hold) circuits, the proposed envelope detector aims to track the variation of the input signal closely in both step-on and step-off transient process, instead of keeping the peak value of $V_{in}$ over time. To meet this demand, a current source is added here, put parallel to the capacitor $C_s$, to speed up the transient process, especially the falling-down transient.

3.1.1 Step-on transient

As Fig. 2 shows, if $V_{in}$ experiences a change of $\Delta V_{in}$, $i_{ds,M1}$ increases by $g_{m,M1} \cdot \frac{1}{2} \Delta V_{in}$ and $i_{ds,M2}$ decreases by $g_{m,M1} \cdot \frac{1}{2} \Delta V_{in}$. Because of the mirror action of M3 and M4, $i_{ds,M3}$ decreases by $g_{m,M1} \cdot \frac{1}{2} \Delta V_{in}$. As a result, the total current going through M7 is $g_{m,M1} \cdot \Delta V_{in}$. This current is mirrored by M7 and M8 (assuming M7, M8 have the same W/L) and then begins to charge $C_s$: $i_c = g_{m,M1} \cdot \Delta V_{in}$. $V_p$ as well as $V_{out}$ will increase consequently. What follows is that the error signal $V_e = V_{in} - V_{out}$ decreases, which results in a reduction of the output current of OTA. Clearly, the charging current is related to the slope of the input signal. The tracking condition persists until $V_{in}$ reaches its peak value. In order to evaluate the delay in the step-on transient, the schematic in Fig. 2 is simplified as shown in Fig. 3, where $C_g$ is the total output capacitance of the OTA, $r_g$ the OTA output resistance. $V_g$ is output voltage of the OTA, $g_{m8}$ the trans-conductance of M8, and $r_{ds,M8}$ and $r_{ds,M10}$ are the output resistance of M8 and M10 respectively. The buffer can be considered as a voltage level shifter. For simplification, the buffer is neglected.

![Fig. 3. Equivalent circuit](image-url)
The transfer function $H(s) = \frac{V_{out}(s)}{V_{in}(s)}$ can be approximated as:

$$H(s) = \frac{V_{out}(s)}{V_{in}(s)} \approx \frac{1}{s^2 + \frac{p_1 + p_2}{p_1 p_2 A_0 g_{m8} r_0} + 1}$$ (1)

where $\frac{1}{p_1} = C_{g'r_g}$, $\frac{1}{p_2} = C_{r_0}$, $A_0 = G_0 r_g$, $C_g \approx 2 C_{g'r_g} r_0$, $r_g = r_{ds.M1} // r_{ds.M3} // g_m r_0$, $r_0 = r_{ds.M8} // r_{ds.M10}$. From equation (1), the damping factor $\xi$ can be easily calculate as $\xi = \frac{p_1 + p_2}{2 \sqrt{p_1 p_2 A_0 g_{m8} r_0}}$. In order to achieve fast-speed response while maintain stability, the damping factor $\xi$ is usually between 0.4 and 0.8, in which case the step response is calculated as

$$v_0(t) = 1 - e^{-\zeta \omega_n t} \left( \cos(\sqrt{1 - \zeta^2} \omega_n t) + \frac{\xi}{\sqrt{1 - \xi^2}} \sin(\sqrt{1 - \xi^2} \omega_n t) \right)$$ (2)

where $\omega_n = \sqrt{p_1 p_2 A_0 g_{m8} r_0}$ is the natural frequency. Adjustment time $t_s$ is used to evaluate the step-on transient response (when $t \geq t_s$, $|v_o(t) - v_o(\infty)| \leq v_o(\infty) \times \Delta\%$) and it is derived as $t_s \approx \frac{4}{\zeta \omega_n}$ (when $\Delta = 2$). According to practical experience, $\xi$ is usually assumed to be $1/\sqrt{2} \approx 0.707$ and then

$$t_s \approx \frac{4}{\zeta \omega_n} = 5.66 \frac{\omega_n}{\omega_n} = 5.66 \frac{C_g C_{g'r_g}}{A_0 g_{m8}} = 5.66 \frac{C_r C_{g}}{G_0 g_{m8}}.$$ (3)

According to (3), which provides design guidance for better transient response performance, in the step-on transient, the delay is mainly affected by the following factors: the value of $C_s$, the output capacitance and trans-conductance of OTA and the trans-conductance of $M_8$. Firstly, $C_s$ plays a very important role in the circuit. In order to make sure the delay time is short (e.g. several ns), the value of $C_s$ has to be small enough. However, this would increase the ripple of the output signal. A compromising value of $C_s$ has to be chosen to make sure that both of the performance (delay and ripple) can meet the challenge. The trans-conductance of the input transistor defines the ability the OTA can transform the voltage change into current. Therefore, a large charging current can be realized if the trans-conductance of the input transistor is large, which will result in quick transient response.

Fig. 4 shows the simulated step-on transient response of the detector. Seen from it, the delay is less than 5 ns.

3.1.2 Step-off transient

If $V_{in}$ experiences a falling edge, $i_{ds.M1}$ decreases. $i_{ds.M2}$ and $i_{ds.M3}$ increase because of the mirror (M3, M4). Therefore, the current going through M7 decreases and then the charging current is getting smaller. However, the mirror (M7~M8) has rectifying behavior, which means that the current of the mirror cannot be reversed. Current cannot flow into the mirror. As a result, the capacitor $C_s$ is unable to be discharged through M7 and M8. An extra discharging path has to be added to the
The current source $I_{B2}$, mirrored by M9 and M10, provides the discharging current for capacitor $C_s$.

Shown in Fig. 5(a), before the input signal declines, $I_a = I_b + I_{C_s}$ (All the current going through transistors is assumed to be its absolute value). As $I_a$ decreases due to the falling-down of input signal, $I_{C_s}$ could become negative when $I_a < I_b$ and then $I_{C_s} = I_b - I_a$ (shown in Fig. 5(b)). $C_s$ is discharged through M10. The discharging current is $I_{C_s}$. When input voltage is becoming small enough, $I_a \approx 0$ and then $I_{C_s} \approx I_b$. Therefore, the discharging current is determined by $I_{B2}$.

Fig. 6 shows the simulated results of the relation between the current value of $I_{B2}$ and the falling-down performance of the detector. The input signal is the amplitude modulation signal with a sine-wave carrier and square-wave signal. The frequency of the carrier and the envelope signal is 3 GHz and 20 MHz, respectively. The current $I_{B2}$ is set to be 8 µA, 10 µA, 15 µA, 20 µA, 25 µA, 30 µA, respectively. From it, we can see that the larger the current $I_{B2}$ is, the smaller the fall-delay will be. As a result, the current source $I_{B2}$ improves the falling-down transient performance of the detector, while the step-on transient performance stays the same. However, as the current $I_{B2}$ increases, the improvement of the delay is not significant any more. Besides, large current will result in large power consumption. Therefore, $I_{B2}$ set to be 30 µA is a reasonable choice.
3.2 Frequency performance

As the operation frequency rises, the detection process will be a little different. Firstly, as is mentioned in section 3.1.1, $I_0$ (the output current of the OTA shown in Fig. 5) is relevant to the slope of the input signal. Assuming the input voltage signal is sinusoidal (i.e. $V_{in} = A \cdot \sin(\omega \cdot t)$), $I_0$ increases with the frequency of the input signal rising, because the slope of the signal ($V'_{in} = \omega \cdot A \cdot \cos(\omega \cdot t)$) becomes large. Nevertheless, $I_a$ (output current of the mirror (M7~M8) shown in Fig. 5) is limited by the frequency due to the parasitic capacitance of the transistor. The bandwidth of the mirror can be approximated as: $BW = \frac{g_{m7}}{2\pi(2C_{gs7} + C_{ds7})} \approx \frac{f_{T7}}{3}$. The amplitude frequency response of the mirror (current gain: $20 \log(I_a/I_0)$) is shown in Fig. 7. Seen from it, $I_a$ decreases with frequency rising, which results in the decay of charging current.

![Fig. 6. Step-off transient of the detector for different discharging currents.](image)

![Fig. 7. Amplitude frequency response characteristics of the mirror](image)

Even though the charging current decreases with the rising of the charging frequency, the detection output could still increase. Because, in the tracking
process, Cs can be charged/discharged more times as the frequency rising and the charging current is larger than the discharging current in each time. This is shown in Fig. 8. The frequency of sinusoidal input is set to be 5 GHz and 10 GHz in Fig. 8. Simulation results (Fig. 8(c)) imply that detection output rises as input frequency increases even though the charging/discharging current decreases. On the other hand, the charging/discharging period is becoming shorter as the frequency rises. Then what follows is that the detection output voltage swings in a small range, which is called the ripple. Seen from Fig. 8(c), the higher the input frequency is, the smaller the ripple of detection output will be.

![Fig. 8](image)

**Fig. 8.** (a) Charging/discharging current when the frequency of input is 5 GHz  
(b) Charging/discharging current when the frequency of input is 10 GHz  
(c) Detection output with different input frequency

Furthermore, the value of capacitor Cs also affects the ripple through the way that small Cs will result in large ripple. Fig. 9 shows the detection output when Cs is different, where the input signal is sinusoidal and the frequency is 3 GHz. From

![Fig. 9](image)

**Fig. 9.** (a) Detection output when Cs = 300 fF  
(b) Detection output when Cs = 600 fF
it, we can see that smaller Cs brings about better transient performance but increases the ripple of the output voltage.

The envelope bandwidth that the detector can handle is another issue that has to be considered. For example, when the input signal is an amplitude modulation signal with a sine-wave carrier and pulse base-band signal, the detector has a limitation that how long the peaking time of the pulse has to be for the detector to recognize. This limitation is mainly decided by the input transistor M1 and the capacitor Cs: \[ \tau = \frac{C_s}{g_m M_1}. \] For instance, the detector can respond to the signal whose envelope bandwidth is hundreds of MHz, if \( \tau \) is equal to several ns.

### 3.3 Stability analysis

Due to the finite bandwidth of OTA, the schematic shown in Fig. 2 may exhibit a damped or even unstable response in the tracking state. The stability in the tracking state can be investigated by evaluating the transfer function \( H(s) = \frac{V_{out}(s)}{V_{in}(s)}. \)

According to equation (1), there are mainly two poles. The first pole \( p_1 \) is contributed by the node A (shown in Fig. 2) between the OTA and the mirror. The other pole \( p_2 \) is contributed by the node C between the mirror and the buffer. Actually, there is another pole \( p_m \) that associated with node B, which is called the mirror pole: \( p_m = \sqrt{2C_{gs} M_4 \cdot g_m^{-1}}. \) However, the mirror pole \( p_m \) can be neglected considering that \( p_m \approx \frac{f_{T4}}{4} \) (\( f_{T4} \) is characteristic frequency of transistor M4) [10].

So the whole system can still be approximated as a second-order system. The transient response can vary monotonically if the damping factor \( \xi \geq 1. \) There will be no overshoot or oscillation in the output response, however the adjustment time could be very long, which will limit the speed of the system. On the other hand, if \( \xi \leq 0, \) the output will oscillate or even diverge. So a compromising way is in the case that the system is in an underdamped state (\( 0 < \xi < 1. \)). Besides, the overshoot \( \delta \% \) is related to the damping factor \( \delta \% = e^{-\frac{\xi}{\sqrt{1-\xi}}} \times 100\%. \) As mentioned before, according to practical experience, \( \xi \) is often set to 0.707 and the overshoot is then 4.32\%. Fig. 10 shows the simulation results of the frequency performance of the
detector, where the input signal is a sinusoidal signal with amplitude of 300 mV. We can see that the operating frequency range covers from 1 GHz to 10 GHz with the output voltage changing no more than 20 mV and simulation results conform to what have discussed in Fig. 8.

4 Measured results

The proposed peak detector is implemented using HuaHong 0.18 µm standard CMOS technology as shown in Fig. 11. The area of the detector part is about 80 µm × 60 µm. The component values are listed in Table I. The total power dissipation of the detector is equal to 2.1 mw.

Fig. 11. Microphotograph of the implemented detector

<table>
<thead>
<tr>
<th>Component</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
</tr>
<tr>
<td>M2</td>
</tr>
<tr>
<td>M3, M4, M7, M8</td>
</tr>
<tr>
<td>M5, M6</td>
</tr>
<tr>
<td>M9, M10</td>
</tr>
<tr>
<td>IB1</td>
</tr>
<tr>
<td>IB2</td>
</tr>
<tr>
<td>Cs</td>
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</table>

Table I. Component values

<table>
<thead>
<tr>
<th>Component</th>
<th>Designed value</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>W = 5 µm, L = 350 nm</td>
</tr>
<tr>
<td>M2</td>
<td>W = 5 µm, L = 350 nm</td>
</tr>
<tr>
<td>M3, M4, M7, M8</td>
<td>W = 5 µm, L = 300 nm</td>
</tr>
<tr>
<td>M5, M6</td>
<td>W = 25 µm, L = 350 nm</td>
</tr>
<tr>
<td>M9, M10</td>
<td>W = 5 µm, L = 1 µm</td>
</tr>
<tr>
<td>IB1</td>
<td>800 µA</td>
</tr>
<tr>
<td>IB2</td>
<td>30 µA</td>
</tr>
<tr>
<td>Cs</td>
<td>500 fF</td>
</tr>
</tbody>
</table>

Fig. 12 illustrates the measured output voltage of the detector when the frequency of the carrier is set to 1 GHz, 2 GHz, 3 GHz, 4 GHz and 9 GHz, respectively. According to Fig. 12, the detector maintained a linear response over a wide input voltage. The envelope detector has an input dynamic range of 19 dB, 19 dB, 18 dB, 18 dB, 19 dB, respectively.

Fig. 13 depicts the detector’s frequency response for a constant input power equal to 1 dBm. The detection output can maintain good consistency for a constant input signal over a range of frequency from 1 GHz to 10 GHz.

Fig. 14 shows the detection process. The input is the amplitude modulation signal with a sine-wave carrier and sinusoidal signal. The frequency of the carrier
Fig. 12. Simulated and measured transfer characteristic of the detector

Fig. 13. Detector frequency response

Fig. 14. Measured result of the detector
and the envelope signal is 2 GHz and 20 MHz, respectively. We can see that the output is successfully tracking the envelope of the input modulated signal. The delay is less than 5 ns.

Table II shows the comparison of this paper with those reported in recent works. It is observed that the proposed detector achieved a wide operation frequency range and fast transient response speed while maintaining low power dissipation with a low cost technology. The dynamic range of the proposed circuit is small when compared with other works. However, it is still suitable for many kinds of receivers.

### Table II. Comparison with previous designs

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Process</th>
<th>Operation Frequency Range</th>
<th>Dynamic Range</th>
<th>Power Dissipation</th>
<th>Response Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>[11]</td>
<td>—</td>
<td>1 Hz~10 MHz</td>
<td>42 dB</td>
<td>4.5 mW</td>
<td>0.4 us</td>
</tr>
<tr>
<td>[6]</td>
<td>0.18 um</td>
<td>100 Hz~1.6 GHz</td>
<td>40 dB@1.6 GHz</td>
<td>6.3 mW</td>
<td>2 ns**</td>
</tr>
<tr>
<td>[12]</td>
<td>0.13 um</td>
<td>200 MHz~4.2 GHz</td>
<td>25.3 dB@3.5 GHz</td>
<td>25 mW</td>
<td>&gt;6 ns</td>
</tr>
<tr>
<td>[13]</td>
<td>90 nm</td>
<td>2.4 GHz</td>
<td>33 dB</td>
<td>0.003 mW</td>
<td>—</td>
</tr>
<tr>
<td>This work</td>
<td>0.18 um</td>
<td>1 GHz~10 GHz</td>
<td>19 dB@9 GHz</td>
<td>2.1 mW</td>
<td>&lt;5 ns</td>
</tr>
</tbody>
</table>

**The response time is simulated for only part of the detector circuit.

## 5 Conclusion

A novel RF envelope detector with ultra-wide operation frequency range and enhanced transient response speed is proposed in this paper. The detector is designed using HuaHong 0.18 µm standard CMOS technology. It consists of an OTA, a mirror for rectifying and a buffer. An extra current source is added in parallel to the capacitor to improve the falling-down transient performance of the detector. Measured results show that the detector can work from 1 GHz to 10 GHz and the transient response time is only a few nanoseconds, which make it suitable for applications such as communication receivers.