# An Adaptive ON/OFF Spiking Photoreceptor

P. Degenaar, T. G. Constandinou and C. Toumazou

***Abstract:*** In this work we present an adaptive spike generator circuit for intelligent vision chips. We have developed pulse frequency modulation spike encoder which is capable of providing very high dynamic ranges with power consumption similar to animal retina. Our circuit is inspired by the ON-OFF opponency algorithm used by the human eye.

***Introduction:*** A major goal of the retinomorphic vision community is the replication of the functionality of the human eye. The eye is capable of detecting more than 8 orders of magnitude of light intensity. It can achieve this with frequency responses of 25Hz in perceptive vision and up to 150Hz in microsaccades, with structures to minimize energy consumption [1].

Inorganic silicon photodiodes are capable of up to 5 orders of magnitude of dynamic range, but are usually only implemented with an 8-bit dynamic range. Early work by Delbrück and Mead [2] led to an adaptive photoreceptor which could detect the contrast regardless of overall light intensity. This chip became the mainstay of the Neuromorphic vision community.

It is however possible to use a spike rate encoding algorithm similar to that in animal vision such as the human eye [4]. By changing from voltage or current space to frequency space, it is possible to achieve wide dynamic ranges at lower power consumption. The major drawback of any integrating system is that the frequency response is low for low light intensities. Here again we can learn from nature by implementing complementary ON and OFF channels [3] [4]. Using ON-OFF opponency, where ON-cells spike at high frequency at high light levels, and OFF-cells spike at high frequency at low light levels, adequate frequency response is acheived, even at low light levels.

***Circuit Description:*** Circuit Description: In previous Neuromorphic vision chips pixel sizes have tended to be around a 100x100µm in size with a fill factor of around 10%. This has tended to work against creating imaging chips with high pixel densities.

Our configuration can be seen in Fig. 1. A single spike encoder is shared between 7 photodiodes, thus increasing the fill factor. The spike encoder can take inputs from individual or all of the photodiodes using a switched arrangement. The current is buffered and mirrored to create on and off channels. In the off channel the current is inverted, such that low photocurrents create high off-currents and vice versa. The two channels then compete by integrating their currents into voltages through capacitance. This voltage is released in the form of a spike once a trigger threshold has been surpassed and the charge collected is reset. To reduce redundancy only the first spike, whether on or off is released and both channels are reset. A complementary output is sent to indicate an ON or OFF spike. Hysteresis is added to stop the circuit oscillating between on and off when the light intensity is close to the threshold between light and dark channels.

***Circuit Operation and Implementation:*** The complete circuit schematic can be seen in Fig. 2. A simple current mirror is used to copy the photocurrent (iphoto) to two separate branches. One copy is fed into a predefined current sink (ibias) which effectively produces the difference of these two currents, i.e. (ibias-iphoto.) This in turn is mirrored to obtain the OFF current. The bias current is chosen such that at maximum light intensity the OFF current is zero, i.e. ibias=iphoto(max). The ON and OFF currents then are used to create an increasing voltage, by means of integrating these into the parasitic capacitance of their respective nodes. High-gain digital buffers are used to threshold detect and the first channel (ON or OFF) to reach threshold is collected through a logic OR gate. An additional output is provided to specify whether the response is ON or OFF by using an RS flip-flop to determine which channel is dominant. Hysteretic feedback is provided to the digital buffers to provide a 10-20% lag on channel selection changeover to prevent rapid channel toggling when the ON and OFF responses are comparable.

On a standard 0.18µm process, the circuit can be implemented into a total silicon area of 880 µm2. For a single 30x30µm photodiode this would lead to a fill factor of 52%.

***Simulation Results:*** The circuit was simulated using the Cadence Spectre (5.0.33usr2) simulator with BSIM 3v3 models for the MOS devices combined with a photodiode model derived from the measured parameters. The simulation results for the individual ON and OFF channels are shown in Fig. 3(a). The slow responses can be seen for the ON channel at low light intensities and the OFF channel at high light intensities. The simulation results of the competing ON-OFF channel spike generator are shown in Fig. 3¬(b). The response shows good variation between light and dark over many orders of magnitude and the final output shows good distinction between ON and OFF channels. The hysteresis at the transitions can also be clearly seen.

The spike interval at maximum spiking rate is 3µs, corresponding to over 500kHz in response when considering that the data is effectively compressed by a factor of two. 500kHz is sufficient to provide 12-bit¬ dynamic range at 50Hz refresh. This maximum firing rate is limited by the parasitic capacitance at the integrating node. This capacitance is mainly due to the large PMOS device sourcing the charge currents, in addition to other smaller devices connected to this node. The spiking rate could be increased by scaling the current mirrors at the expense of quiescent power consumption.

***Measured results:*** The spiking photoresponse of the fabricated circuit has been measured over an incident irradiance range of 50nW/cm2 to 5µW/cm2. The spiking rate has been measured to be linear over this photocurrent range. Furthermore, the bias current level adjusts the ON-OFF changeover point as expected. Both the basic spiking photoresponse and adaptive ON-OFF changeover behaviour is illustrated in Fig. 4.

***Power Consumption:*** This can be attributed to two sources: (i) the static power due to the continuous current flow in the current mirrors and (ii) the dynamic power due to the digital switching. The quiescent current consumption is approximately 3nA. The dynamic current consumption is 370μA per 1.5ns spike in a 3μs window. Thus the energy consumption per spike is 500fJ. Given the competition between the ON and OFF channels the minimum frequency the circuit will operate at is 500Hz. In this regime the quiescent power consumption is 5nW compared to 125pW for the spiking. However for most of the operation at 5kHz to 500kHz it is the quiescent power consumption which will dominate. Thus, averaging this quiescent power over the pulse train gives 20.5pJ of energy per spike, which is comparable to the bit-energy of 2-20pJ/bit for the blow fly retina [1].

***Discussion:*** Our photoreceptor circuit is capable of adaptively providing very high dynamic range or response frequencies. We envisage its use for autonomous robotic vision applications, where the robot would wish to switch between different modes of vision such as high temporal-low spatial response and vice a versa. The asynchronous nature of this system ideally suits the output for encoding through existing protocols such as address event representation [5] or addressing pulse counter protocols. We are presently working on information compression algorithms to achieve this.

***Conclusion:*** We have presented a biologically inspired technique to obtain optical information from vision chips using spike rate encoding. Both high frequency responses and dynamic ranges are possible. The power consumption is 20pJ per spike. A chip has been sent out for fabrication and further work is being carried out on the switching and tomography protocols.

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***Figure Captions:***

Fig. 1 System algorithm

Fig. 2 Basic circuit topology

Fig. 3 Simulation results illustrating incident photocurrent, integrating nodes and spiking output for: (a) individual ON/OFF response and (b) competing ON/OFF channel spike generators.

Fig. 4 Measured photo-response for the adaptive ON-OFF spiking photoreceptor circuit. Illustrated is the spike rate to incident light power, for various bias current levels.

***Figure 1:***

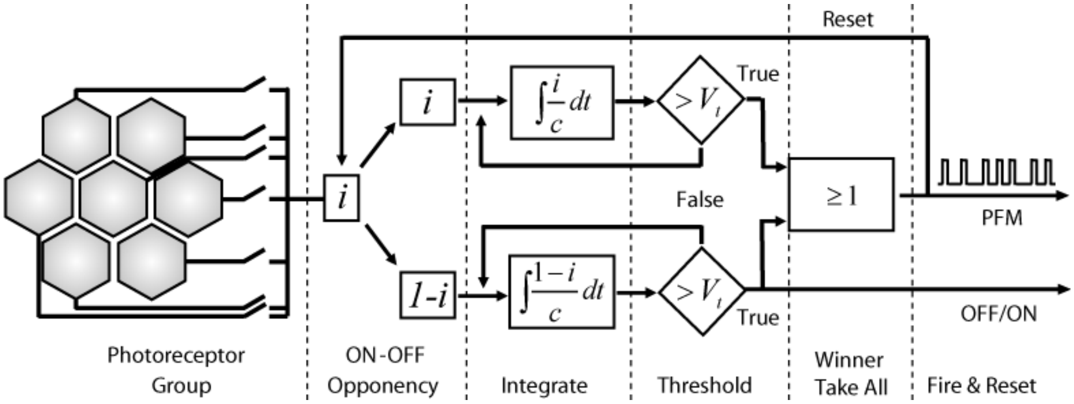

Reset
True
$i$
$\int \frac{i}{c}\,dt$
$> V_t$
$\geq 1$
PFM
False
$i$
$1\text{-}i$
$\int \frac{1-i}{c}\,dt$
$> V_t$
True
OFF/ON
Photoreceptor Group
ON-OFF Opponency
Integrate
Threshold
Winner Take All
Fire & Reset

***Figure 2:***

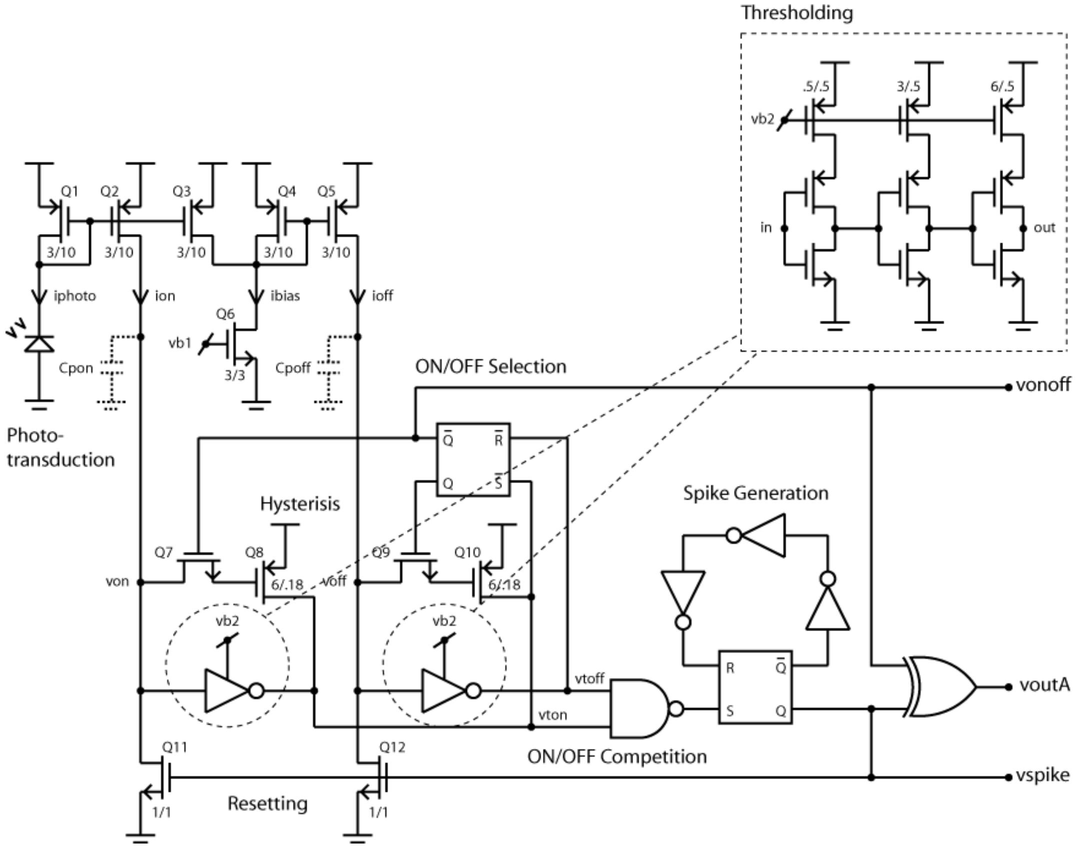
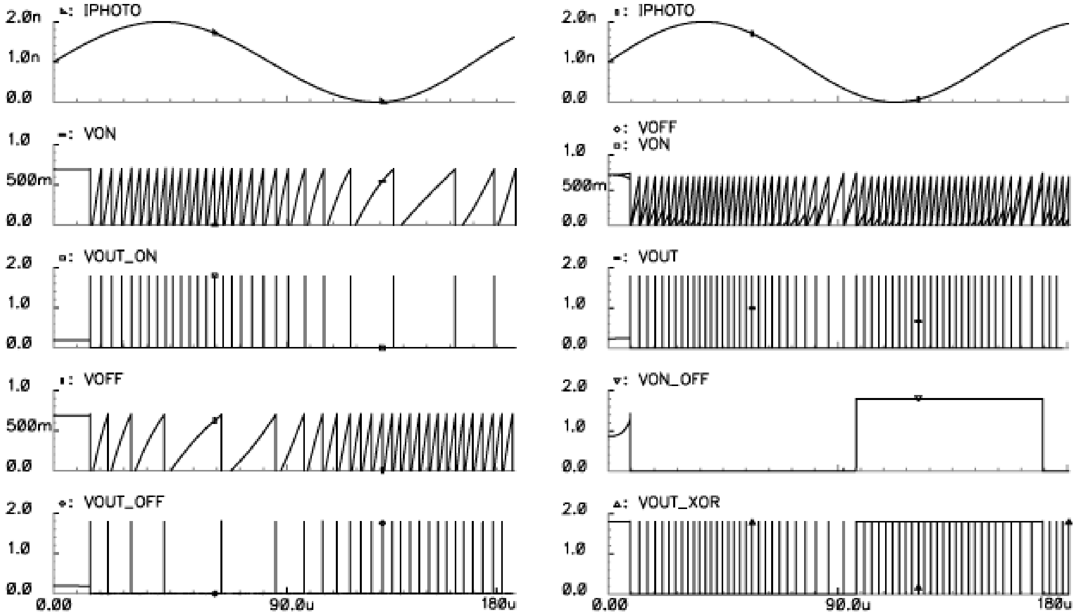

Thresholding
.5/.5
3/.5
6/.5
vb2
in
out
Q1
Q2
Q3
Q4
Q5
3/10
3/10
3/10
3/10
3/10
iphoto
ion
ibias
ioff
Q6
vb1
3/3
Cpon
Cpoff
Photo-
transduction
ON/OFF Selection
vonoff
Q̄
R̄
Q
S̄
Hysterisis
Q7
Q8
Q9
Q10
von
6/.18
voff
6/.18
vb2
vb2
Spike Generation
R
Q̄
S
Q
vtoff
vton
voutA
ON/OFF Competition
Q11
Q12
1/1
1/1
Resetting
vspike

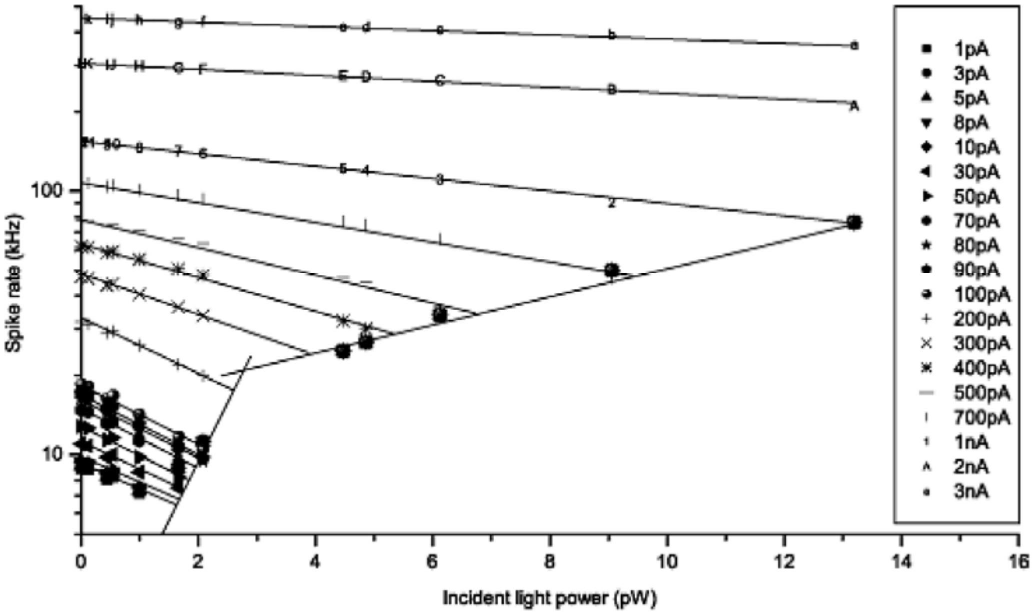
***Figure 3:***



(a) Individual ON/OFF

(b) Competing ON/OFF

***Figure 4:***


Spike rate (kHz)
100
10
0
2
4
6
8
10
12
14
16
Incident light power (pW)
■ 1pA
● 3pA
▲ 5pA
▼ 8pA
◆ 10pA
◀ 30pA
▶ 50pA
● 70pA
★ 80pA
⬟ 90pA
◒ 100pA
+ 200pA
× 300pA
✳ 400pA
— 500pA
| 700pA
1 1nA
A 2nA
a 3nA