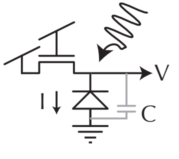
SELF-BIASING LOW POWER ADAPTIVE PHOTORECEPTOR

T. Delbruck and D. Oberhoff, *Inst. of Neuroinformatics, ETH/Univ. Zürich, Switzerland*

ABSTRACT

This report describes a self-biased 5-transistor, 2-capacitor, adaptive logarithmic photoreceptor circuit. The photoreceptor uses its photocurrent, multiplied by a constant factor, to bias its forward amplifier. As a result, power consumption scales with illumination and takes on low values under typical illumination levels. This scaling enables solar powered operation, because power consumption scales with available power. As in earlier circuits, the photoreceptor has an adaptive logarithmic response: it has a bandpass characteristic with low gain for DC (including mismatch) and a higher gain for transient changes in contrast. The gain-bandwidth product is higher than for a passive architecture by a desired multiple. Stability criteria, sharing the bias among many photoreceptors, and measurements from a fabricated chip are shown.

1. INTRODUCTION



A passive logarithmic photoreceptor that is powered entirely by the photocurrent (*left*) has a gain-bandwidth product that is determined by the photocurrent and the capacitance. The gain arises from the source conductance *g* of the subthreshold feedback transistor and is U_T (the thermal voltage) per e-fold of photocurrent. The bandwidth is approximately $g/C = I/(U_T C)$, so the GBW product is I/C. This remains true if a passive feedback network is used, for example, to make a bandpass response to increase the gain without amplifying the mismatch. Increasing the gain will decrease the bandwidth. A mainstream CMOS process has photodiode (well) capacitance of about 100aF/um^2. Under indoor illumination (100lux), surface reflectance of 20%, *f*/3 optics, and quantum efficiency of 50%, photocurrents will be about 1fA/um^2. If the passive feedback amplifies the output signal by 10, then the bandwidth will be about 10Hz. At lower illumination, the bandwidth is reduced even more. This is too slow for many applications. In addition the output impedance is extremely high because it is driven only by the photocurrent.

The self-biased photoreceptor proposed here (Figure 1) operates in continuous-time. A photocurrent is continuously transduced to a voltage and usually forms the input to a local computation. In addition to the desirable properties of earlier photoreceptor circuits—adaptation and suppression of mismatch, logarithmic response, and speedup relative to a passive architecture—the self-biased photoreceptor's active amplification is powered proportional to the illumination, so its power consumption scales directly with illumination, taking on very low values under usual conditions. An array of 100x100 photoreceptors that are each statically biased so they burn 1uW, for example, consumes 10mW of power. The same array using self-biased photoreceptors in an office environment, with photocurrents of 100fA and a current multiplication of 100, will consume about 100nW, saving a factor of 10^5 in power consumption.

2. CIRCUIT

Figure 1 shows the self-biasing photoreceptor circuit. It differs from previous photoreceptor circuits [1;2] by mirroring a multiple *M* of the photocurrent (I_{bg}) to power the forward amplifier (I_b). There are no external biases.

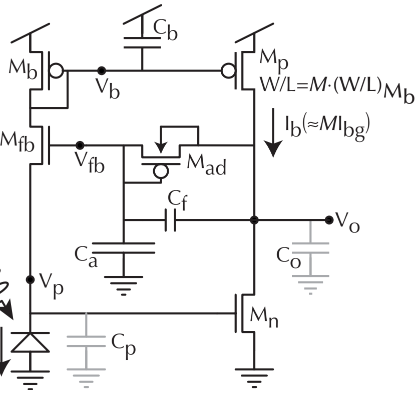


Figure 1 Self-biased photoreceptor circuit. C_p and C_o are parasitic.

Previous adaptive photoreceptor designs used a static I_b, which needed to be large enough to make the loop sufficiently stable at the highest illumination level. The *Q* of the bandpass resonance peaking was a strong function of the illumination. The input node V_p has a time constant τ_p that is determined by the input capacitance C_p and the source conductance $g_p = I_{bg}/U_T$ of M_{fb}. The forward amplifier formed from M_n and M_p needs to be fast enough at all illumination levels to keep up with changes at the input node. As a result, much power is wasted at lower illumination levels if I_b is a constant value that is high enough for high illumination levels. The new design uses an optimal amount of power at each illumination level by scaling the amplifier bandwidth proportional to the bandwidth of the input node.

Capacitor C_b ensures stability; if it is too small the circuit becomes a limit-cycle oscillator. Making C_b too big makes half the final response to a step change of illumination very slow. There is an optimum value of C_b that results in a kind of optimum response, which will be discussed later. Because V_b is filtered with diode-capacitor dynamics, its dynamics is always matched to dynamics of other branches in the circuit.

A single M_b can be shared among an array of *N* photoreceptors to provide a common bias that is proportional to the summed photocurrent (Figure 2). The cost of providing adaptive self-biasing is then the cost of a single transistor and the wire connecting all the drains of the M_{fb}'s. The bias current multiplier *M* is provided, at least partially, by the plurality of photoreceptors rather than an explicit current mirror ratio. The summed photocurrents are lowpass-filtered by the diode-capacitor mirror to generate the shared bias voltage V_b. As before, this diode-capacitor filtering means that the time-constant of the filtering scales with the time constants of other nodes in the circuit. A small static current I_{b0} is added to ensure that the amplifiers are always turned on enough that they can keep the M_{fb} turned on, to avoid the condition that all the photocurrent is supplied by forward biasing the M_{fb} source-substrate junction, instead of through its channel. C_b should be connected to the positive supply, so that power supply noise is not amplified directly by the high gain at V_b.

Because the bias in the Figure 2 configuration is shared, there is a coupling between the photoreceptors. A change of photocurrent at one receptor will affect the outputs of all of them. Therefore, it is only meaningful to use differential comparison between photoreceptor outputs, or between photoreceptors and their average output.

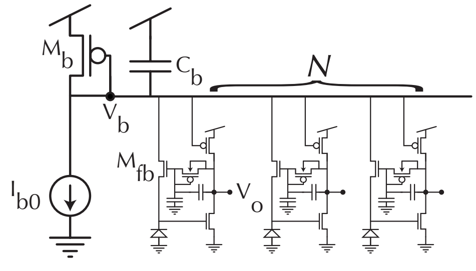


Figure 2 Sharing the adaptive bias.

The operation of the basic feedback loop is as follows. We consider the photocurrent $I_{bg}+i$ as being composed of a steady background I_{bg} and a varying small-signal component i. This photocurrent is logarithmically transduced to V_p at the source of M_{fb}. If the photocurrent increases, V_p decreases logarithmically. V_p is amplified by M_n and M_p to form the output V_o. V_o is fed back to V_{fb} through the adaptive element M_{ad} and the capacitive divider formed by C_f and C_a. At very low frequencies, M_{ad} acts as a short, providing unity-gain feedback and resulting in a low-gain response. At higher frequencies, feedback gain is reduced to the capacitive divider ratio, so the overall gain of the photoreceptor is increased. This feedback arrangement provides the adaptive properties of the photoreceptor. The photoreceptor amplifies DC signals (including transistor mismatch) with low gain, and transient signals with high gain, similar to biological photoreceptors. At the same time, the response is logarithmic at all intensities, so the gain is inversely proportional to illumination. This gain control provides invariance to absolute illumination. Gain control is local and self-contained. The gain from i/I_{bg} to V_o is determined by the ratio between C_f and C_a.

V_{fb} stores the adaptation state. Adaptive element M_{ad} has a sinh()-like I-V relationship, resulting in nonlinear adaptation. Small signals result in very slow adaptation, while large signals cause rapid adaptation. Liu [3] described an alternative implementation for M_{ad} that is tunable. The implementation tested for this report uses the MOS-bipolar element from [1], shown in Figure 3. It has the virtue of simplicity and is immune to parasitic photocurrent effects and DC operating point variations in conductance. Its main drawbacks are (sometimes) the nonlinearity, and the lack of means for dynamically controlling its conductance characteristics.

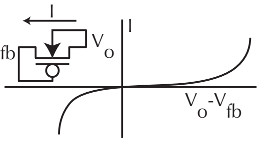


Figure 3 Adaptive element M_{ad} and its I-V curve

On short time scales, C_b holds the amplifier bias current I_b constant, so the operation of the self-biased photoreceptor is similar to those reported previously. The DC gain of the self-biased photoreceptor is double that of previous designs, because the bias current of the forward amplifier is no longer constant, but proportional to the photocurrent.

The output impedance of this self-biased photoreceptor is determined by the photocurrent, so it typically will be quite high compared with statically-biased photoreceptors.

This high impedance should be considered when using the photoreceptor to drive later circuits that can form a feedback circuit with the photoreceptor.

3. STABILITY

The photoreceptor is unconditionally unstable if capacitor C_b is too small. This instability arises from a positive feedback loop introduced by the adaptive bias. An increase in photocurrent causes V_p to decrease, which causes the output V_o to rise through the decrease in current in M_n. The increase at V_o causes an additional increase in feedback current through the gate V_{fb} of M_{fb}. This increased current is mirrored back through M_p, causing a further increase in the output voltage. This increase in output continues until the output hits the positive rail. The complementary actions cause a reset to ground. The result is a limit-cycle oscillation that continues forever.

Capacitor C_b stabilizes the circuit by delaying the positive feedback to the photoreceptor output. Solving for the transfer function assuming that we ignore the adaptation conductance but include the input, bias, and output nodes, we obtain the 3rd order system

$$H(s) = \frac{v_o(s)/\mathrm{U_T}}{i(s)/\mathrm{I_{bg}}}$$

$$= \frac{\frac{1}{a}(R\tau s+2)}{\frac{(\alpha\tau s+1)(R\tau s+1)(\tau s+1)}{aA} + [(R-1)\tau s+1]}$$

$$R = \frac{\mathrm{C_b}}{\mathrm{C_p}}, \qquad \tau = \frac{\mathrm{C_p I_{bg}}}{\mathrm{U_T}}, \qquad \alpha = \frac{\mathrm{C_o}}{\mathrm{C_p}}\frac{A}{M}$$

$$a = \frac{\kappa \mathrm{C_f}}{\mathrm{C_f+C_a}}, \quad A = \text{voltage gain from } \mathrm{V_p} \text{ to } \mathrm{V_o}$$

All the terms in s scale with the same τ, the time constant of the input node; τ scales inversely with illumination. We have not been able to find a closed-form expression for the required C_b to ensure stability because this 3rd order system is very complicated to analyze analytically. However, a typical root locus plot is shown in Figure 4, where the parameter that is varied is the ratio R=C_b/C_p, holding other parameters constant at reasonable values. The three poles always appear as a single negative real and a conjugate pair. An "optimal" set of poles is indicated by the arrows. By optimal, we mean that there is a balance between the values: all the poles have roughly the same time constant. Under these conditions, no time constant is dominant and the transfer function is a reasonable bandpass filter with some amount of peaking.

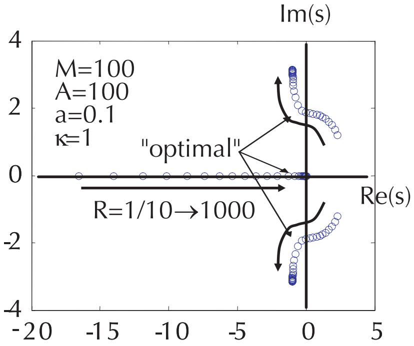


Figure 4 Root locus plot for photoreceptor transfer function. The ratio R=C_b/C_p is varied. Other parameters are shown in the inset.

4. SIMULATION RESULTS

A SPICE transient simulation of the photoreceptor is shown in Figure 5. Realistic levels of photocurrent and photodiode capacitance were used. Photocurrent input that steps over 6 decades, with small-signal square wave variation during each step, were used to test the large signal response of the circuit. The supply current is M times the photocurrent. The response at the output of the photoreceptor (V_o) is shown along with the photodiode voltage (V_p) and are compared with the voltage from a passive source-follower photoreceptor (V_{sf}). Within each illumination level, the photoreceptor adapts itself to the background illumination and outputs a response that amplifies the small-signal variation in the photocurrent much more than the DC component. The gain-bandwidth product of the adaptive photoreceptor is much higher than that of the passive source-follower sensor.

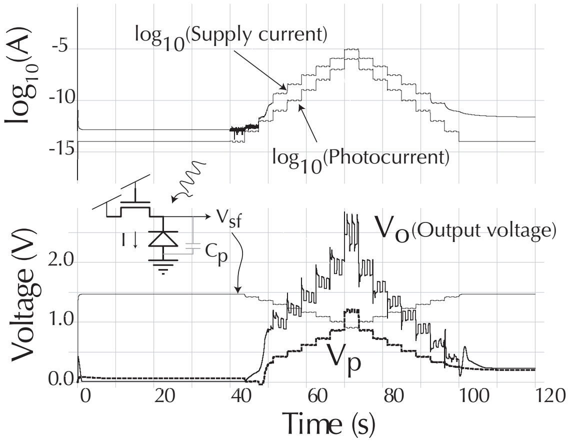


Figure 5 Transient simulation.

5. TEST RESULTS

A fabricated chip in 1.6u technology has an array of 7 self-biased photoreceptor circuits sharing a single M_b, as in Figure 2. C_b is off chip. Figure 6 shows the response of a single receptor of this array to step increases of intensity of fixed contrast, over a range of 5 decades of starting illumination. As we expect, the time-scale of each response scales inversely with its illumination level.

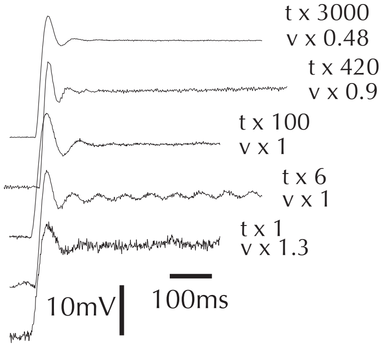


Figure 6 Step responses over 5 decades background photocurrent, scaled as shown.

Figure 7 shows measured frequency responses over 4 decades of background illumination. The frequency response largely scales with illumination. The adaptation corner at low frequency also scales with illumination, because an unintended hole in the metal over M_{ad} generates parasitic photocurrent to bias the adaptation conductance. Under high illumination, M_{fb} goes above threshold, increasing the gain slightly, and at low illumination, dark current slightly reduces the gain. These frequency responses are compared with the statically biased configuration; they differ significantly only in the amount of peaking.

6. CONCLUSION

We think that this self-biased photoreceptor could be useful in very low-power systems, such as solar powered sensors or visual prosthetics. The particular topology shown here is not essential; transducers with variable gain—and hence bandwidth—at the input stage can benefit by adaptively biasing the feedforward amplifier. The present implementation is a compact and practical photoreceptor for fairly dense integration, and we are using it on a chip that is shipping to paying customers[1].

7. ACKNOWLEDGEMENTS

Funded by the Univ. of Zürich and ETH Zürich. The self-biasing circuit was conceived at the Telluride Neuromorphic Engineering Workshop.

8. REFERENCES

[1] Delbrück, T. and Mead, C. A. Analog VLSI adaptive logarithmic wide-dynamic-range photoreceptor. vol.4, 339-342. 1994. London. 1994 IEEE International Symposium on Circuits and Systems.

[2] Kramer, J., "An integrated optical transient sensor," *IEEE Trans. on Circuits and Systems II*, vol. 49, no. 9, pp. 612-628, Sept.2002.

[3] Liu, S. C. Silicon retina with adaptive filtering properties. Jordan, M. I., Kearns, M. J., and Solla, S. A. vol.10, 712-718. 1998. MIT Press. Advances in Neural Information Processing Systems 10. Jordan, M. I., Kearns, M. J., and Solla, S. A.

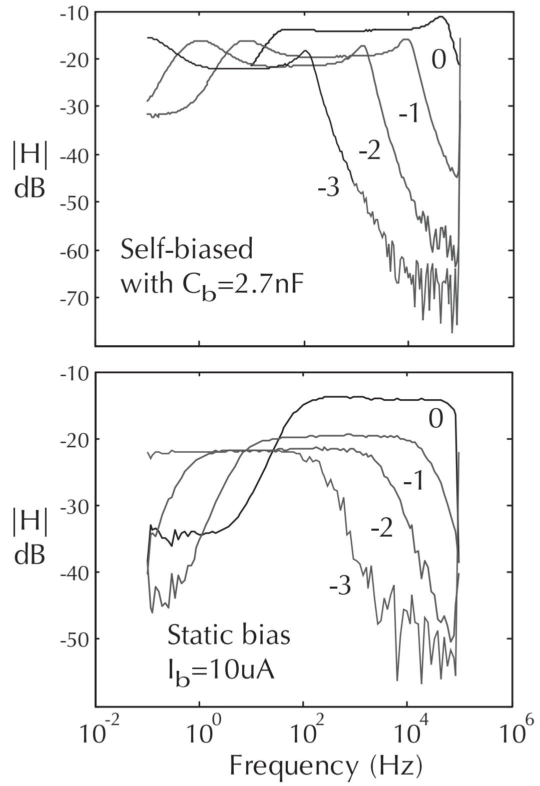


Figure 7 Measured frequency responses with C_b=2.7nF compared with using a static bias. The legend shows the $\log_{10}$ background illumination.

---

[1] www.ini.unizh.ch/~tobi/friend