Cricket: A Self-Powered Chirping Pixel Supplemental Material

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1 CRICKET CIRCUIT DETAILS

Here we provide a detailed explanation of the cricket circuit in Fig. 1. When the photovoltaic cell is exposed to light, it charges capacitor C_1, and voltage V_c begins to rise. At some voltage, the comparator comes to life. At that point, the reference (regulated) voltage V_r is smaller than the voltage V_1 and hence the output V_o of the comparator is 0. Since V_c continues to rise, at some point, V_1 will exceed V_2, and the comparator output V_o goes from 0 to V_c. This activates the oscillator, which puts out an RF frequency (in the GHz range). The frequency f_{id} of the oscillator output, which is the identifier of the cricket, is determined by the voltage V_f, which, in turn, is determined by the resistors R_t and R_b and the capacitor C_2. In our implementation, f_{id} is preset by selecting the resistor R_b.

Although the oscillator is now active, it is not yet connected to the antenna due to the switch S. The closing of this switch is delayed by R_4 and C_3. This delay is introduced to allow the preset voltage V_f to stabilize and ensure the frequency applied to the antenna is precise and stable. In the current implementation, this delay has been set to roughly 10 µs. After the delay, the oscillator is connected to the antenna, which transmits an RF chirp for about 30 µs. This chirp duration is limited solely by the fact that the oscillator is, by far, the highest power consumer in the circuit. Hence, while the oscillator is active, V_c falls rapidly until V_1 goes lower than V_2, the comparator output goes to 0, and the oscillator shuts down. At this point, C_1 begins to recharge and V_c rises again.

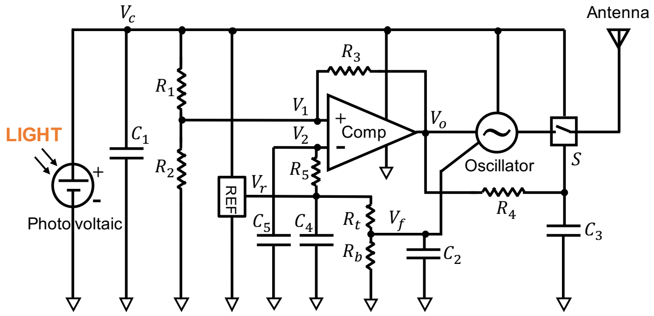

Fig. 1. **Cricket circuit.**

Table 1. **List of components in the circket circuit.**

Component	Value
C_1	3.3 µF
C_2	10 µF
C_3	220 pF
C_4	0.1 µF
C_5	1 µF
R_1	6.2 MΩ
R_2	10 MΩ
R_3	100 MΩ
R_4	100 kΩ
R_5	1 MΩ
R_t	4.02 MΩ
R_b	10 – 100 MΩ (adjustable)
Photovoltaic	Panasonic AM-5610CAw-DGK-T
Voltage Reference	ABLIC Inc. S-1318D18-M5T1U4
Comparator	Texas Instruments TLV3691
Oscillator	Analog Devices MAX2752
Switch	Analog Devices ADG 901
Antenna	Taoglas FXP 29 (2.04 – 2.10 GHz)

Our current implementation uses off-the-shelf passive (resistors and capacitors) and active (comparator, oscillator and switch) components. The values and model numbers of the components we used in our prototype are given in Tab. 1. The resistor R_3 introduces hysteresis in the comparator output. It can be lowered to increase the length of the chirp. In our case, however, we want the chirp to be very short and hence we have used a large value (100 MΩ).

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Table 2. **Current drain of components in the cricket circuit.**

Component	Chirping (nA)	Sleeping (nA)
Oscillator	10^7	200
Voltage divider, R_1 and R_2	181	181
Voltage divider, R_t and R_b	116	116
Switch	100	100
Voltage reference	95	95
Comparator	75	75
Total	10^7	767

2 POWER MODEL DETAILS

We have estimated the power consumption of a cricket from the typical current drain of each of its components. In Tab. 2, we list the current drain for each component when the cricket when the cricket is chirping and sleeping (not chirping). When the cricket is chirping, the oscillator consumes 10 mA during its 40 µs chirp. When the cricket is sleeping, the active components and voltage dividers consume 767 nA.

The power consumed by each component is also function of the voltage. We will assume a constant voltage $V_c = 2.9$ V to compute the power consumption from the currents in Tab. 2.[1] This is a valid choice for all components, including those powered by V_r, because the voltage reference is a linear regulator. Using this voltage, the power consumed while chirping and sleeping is:

$$P_{chirping} = 29.0 \text{ mW}, \quad P_{sleeping} = 2.23 \text{ µW}. \tag{1}$$

A typical cricket chirps roughly 0.1 chirps per lux, per second, and each chirp lasts 40 µs. From these facts, we can compute the time spent chirping and sleeping as a function of the light level, L lux, in a time interval T seconds as:

$$T_{chirping} = 4LT \cdot 10^{-6} \text{ s}, \quad T_{sleeping} = T - T_{chirping} \text{ s}. \tag{2}$$

Now, the average power consumption is given by:

$$P = \frac{T_{chirping} \cdot P_{chirping} + T_{sleeping} \cdot P_{sleeping}}{T} \text{ W}. \tag{3}$$

We can rewrite P as a function of the light level, L lux, as $P = \alpha L + \beta$, where $\alpha = 116$ nW/lux and $\beta = 2.23$ µW.

3 eTRANSITION GLASS CIRCUIT DETAILS

Here we detail the eTransition glass circuit in Fig. 2, a self-powered circuit inspired by cricket that drives a liquid crystal (LC) light valve. As mentioned in the main paper, the first part of the cricket circuit in Fig. 1 – from the photovoltaic to the comparator output – is essentially a self-powered pulse generator with a very low duty cycle. In place of the oscillator, we use an inverter that converts V_o to an AC pulse train in order to drive the LC valve. The transmittance of the LC valve is therefore inversely proportional to the incident light.

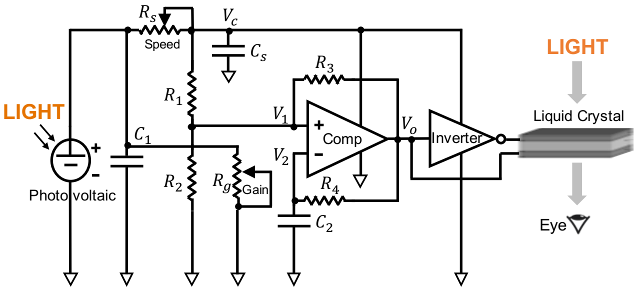

Fig. 2. **eTransition glass circuit.**

Table 3. **List of components in the eTransition glass circuit.**

Component	Value
C_1	3.3 µF
C_2	100 pF
C_s	0.1 uF
R_1	10 MΩ
R_2	10 MΩ
R_3	10 MΩ
R_4	10 MΩ
R_g	100 MΩ
R_s	1 kΩ
Photovoltaic (×6)	Vishay BPW34
Comparator	Texas Instruments TLV3691
Inverter	Texas Instruments SN74AUP1G04
LC Light Valve (×2)	Adafruit PID 3627

As with the cricket, when the photovoltaic is exposed to light, the voltage V_c begins to rise. Initially, the comparator output V_o is 0. When V_1 exceeds V_2, V_o jumps to V_c. At this point, V_2 begins to rise due to R_4 and C_2. At some point, V_2 exceeds V_1, and the comparator output V_o drops to 0. The comparator output V_o is therefore a square wave and its duty cycle is determined by R_1, R_2 and R_3. We have chosen these resistors such that the duty cycle is 50%. The frequency of the square wave is determined by R_4 and C_2. Most importantly, the peak value of the square wave is proportional to the intensity of light falling on the photovoltaic. Table 3 lists the component values used in this circuit.

We now have V_o varying between 0 and V_c. However, we need an AC voltage which includes a reverse in polarity. This is achieved by using the inverter. Both the output of the comparator and the output of the inverter have a push-pull configuration. These outputs are used to, in effect, create an H-bridge, which results in the LC valve seeing an AC voltage that flips between (V_o, 0) and (0, V_o), where V_o is proportional to the incident light intensity.

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[1] Technically, V_c is not a constant but a sawtooth wave shown in Fig. 4 of the main paper. To approximate the power consumption, we conservatively use $V_c = 2.9$ V, the threshold voltage at which the cricket chirps.