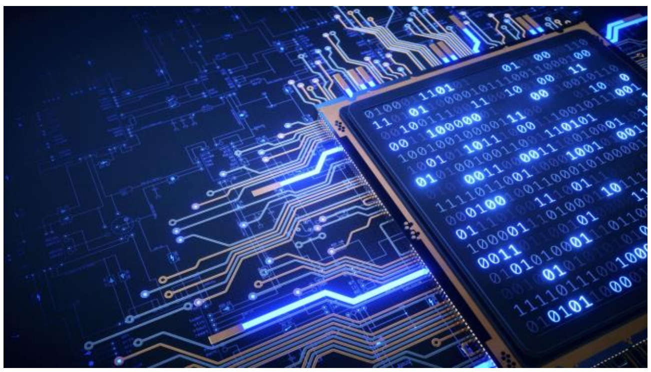

EXPLORING LIGHT SENSITIVE CIRCUITS

LM393 OP Amp as a comparator & Schmitt Trigger

ABSTRACT

Ever wondered how your porch light turns on automatically when it gets dark? Are you curious how the automatic headlight dimmer system in your car works? This paper shows you how you can build such a circuit with some simple electronic components and including an operational amplifier integrated circuit (IC). We will examine how the circuit works by using both simulation software and oscilloscope images. We will also examine how to add something called hysteresis to our circuit to make it much more stable.

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Applied Robotics & Embedded Programming

Introduction

There are numerous situations where we turn on a device when it gets dark or when it gets light outside. You may want to build an automatic security lighting system using a *light-dependent resistor* (LDR), for example. An LDR responds to light intensity. It acts like a variable resistor in that the light level causes it resistance to change.

Figure 1-1 shows the relationship between the LDR's resistance and light levels it detects. These components vary widely so be sure to use an ohm meter to measure yours before using it. It is important to know how it works. In other words, does its resistance *increase* or *decrease* when you shine a flashlight on it?

When I tested mine, as the light got brighter the resistance in the device dropped to around 100 ohms. Conversely, when I covered the LDR with my hand, its resistance increased to around 20Meg ohm.

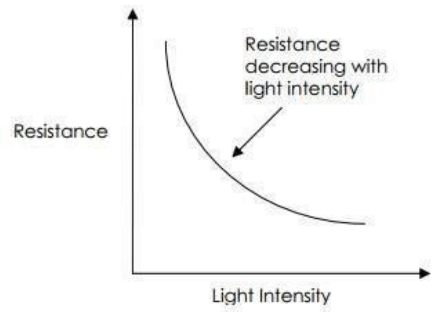


Figure 1-0-1: LDR changes resistance based on the light level it detects.

Using the LM393 OP-Amp as a Comparator

We will start by looking at the basic circuit that lets us acommplish this. The LM393 is a special version of the Op-Amp. It is designed to respond faster to changes at its inputs and works quite well in this scenario. A comparator circuit monitors two voltages and compares them to find which one is larger. The Op-Amp is an analog device that produces a digital output. The voltage from our LDR is compared to a reference voltage. When the voltage from the LDR is greater than the reference, it outputs a HIGH (5V) signal that can be used to turn on my porch light. If the LDR voltage is less than the reference voltage, its output goes LOW (0V).

To summarize, when the non-inverting (+) input is greater than the minus (-) input, the output goes HIGH (+). When the inverting (-) input is greater, the output goes LOW (-).

The circuit in Figure 1-2 shows how this works. When the light falls, the LED is turned on. The LDR and 33K resistor form a voltage divider. The IC compares the INVERTING input at PIN 2 with the NON-INVERTING input voltage at PIN 3. Our circuit uses a 10K pot to set a reference voltage or *set point* for the LM393 and the output of the pot is tied to the non-inverting pin (+).

The output of the LDR's voltage divider is tied to the inverting input (-). When the LDR is exposed to darkness and its resistance increases, the voltage at pin 2 increases. If it is above the reference voltage at pin 3, the output goes LOW and the LED turns on. The LED's cathode has a path to ground inside the chip in this condition.

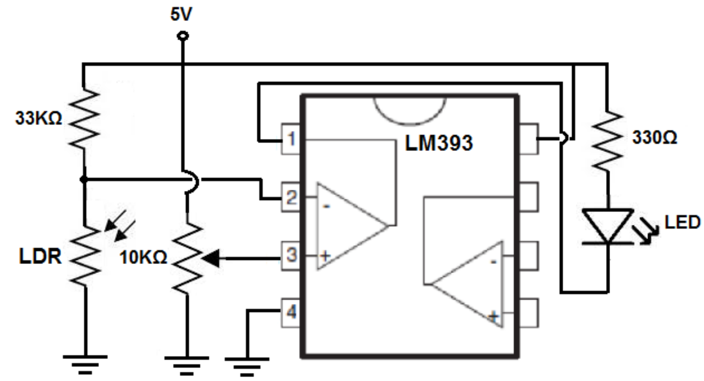


Figure 1-2: LDR Light controller with adjustable sensitivity level.

On the other hand, in bright light, the LDR's resistance drops very low and so the voltage is reduced and pin 2 is lower than pin 3. When this happens, the LED goes off because the LM393 output is HIGH. Without a path to ground, the LED turns off.

But what if we want to turn on something larger than an LED? Well, in the past we used a transistor to source/sink current for larger loads like motors or relays. We will look at that solution next.

Basic LDR Comparator Circuit Relay Driver

In class, I will show you how the circuit in Figure 1-3 works. The simulation will show how sensitive op-amps are. Remember, op-amps measure the difference between its inputs. When configured as an amplifier, they amplify the voltage difference thousands of times. They are extremely sensitive and the slightest difference in the input signals triggers a response.

My relay driver circuit uses a 2N3906 PNP transistor to drive the relay because like the *Arduino*, the LM393 cannot source/sink more than about 20mA. We have used transistors in this role before because they can handle more current.

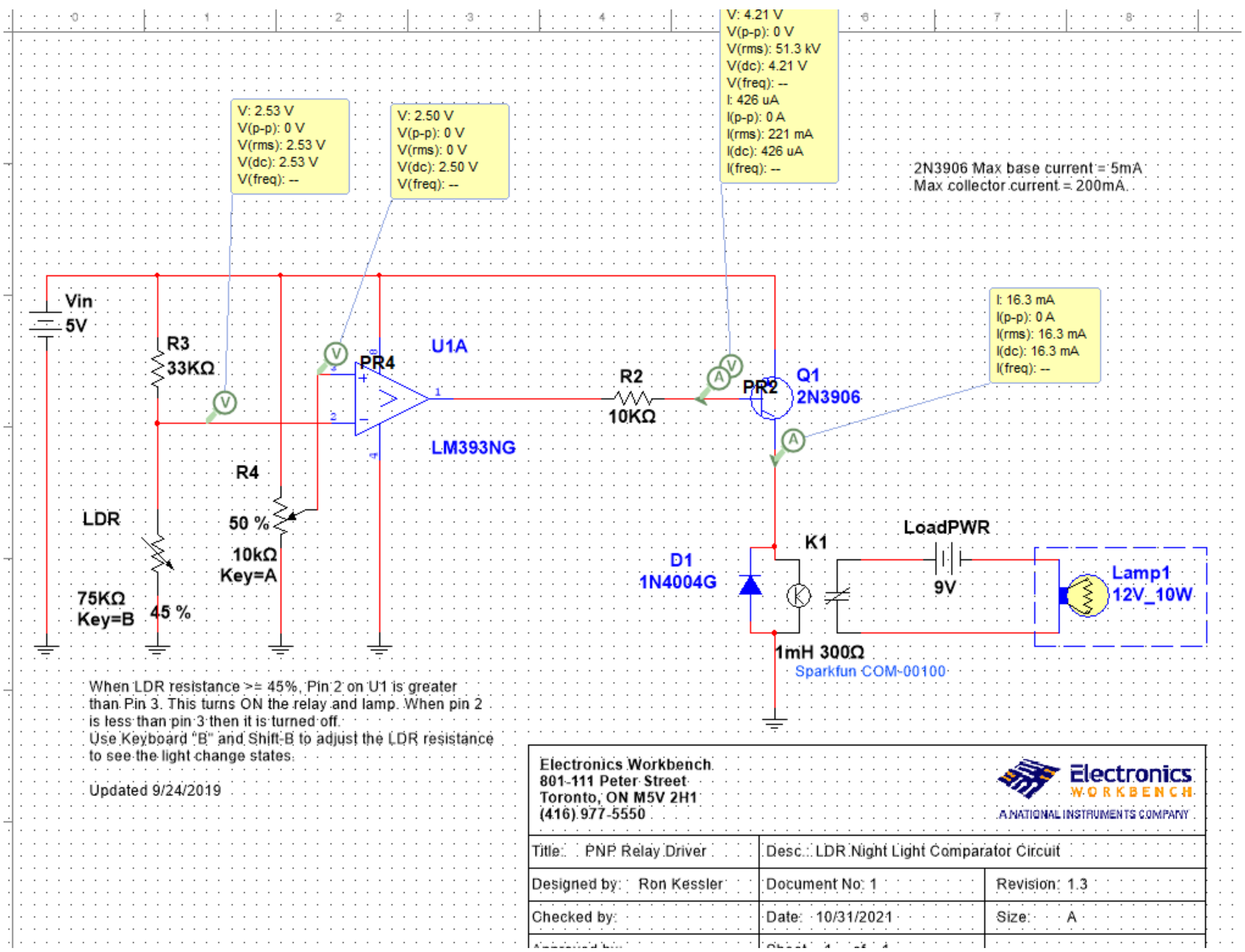


Figure 1-3: Output from the LM393 drives a transistor that controls a relay to turn on a higher voltage light.

How to Minimize "Chatter" in LDR Circuits: Introduction to Hysteresis & the Schmitt Trigger

You may recall that mechanical switches cause "point-bounce" when they open or close. We discovered that this played havoc with sensitive circuits. We also found this same problem with transistors. Well, it should be no surprise that the LDR also causes unstable signals in certain conditions. But since there is no mechanical device inside the LDR, this noise is called "chatter" instead of point bounce. It means the op-amp gets unstable voltage readings from the sensor and doesn't know what to do. So, it outputs random pulses which cause our porch light to flicker. A technique called ***hysteresis*** solves this chatter issue. Let's take a closer look.

Figure 1-4 shows this phenomenon. Without Hysteresis the signal will bounce near the threshold. (Courtesy of Texas Instruments).

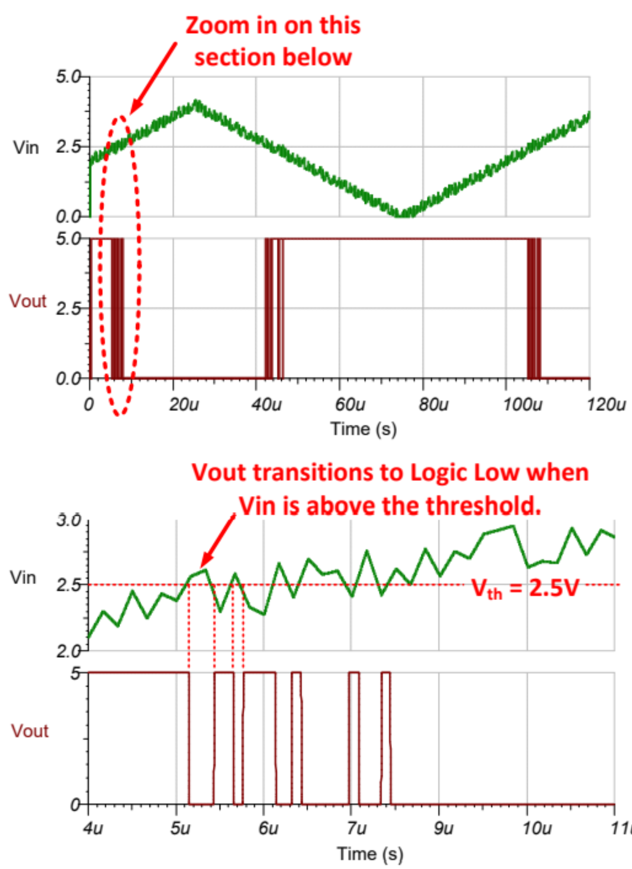


Figure 1-4: False triggering (chattering) occurs when the LDR does not produce a steady voltage. The inputs to the op-amp are changing when the threshold between light and dark is blurred.

When the resistance of the LDR approaches the trigger/reference voltage of the comparator, it false triggers a lot. This is analogous to switch bounce that is seen with mechanical switches/relays. See Figure 1-5.

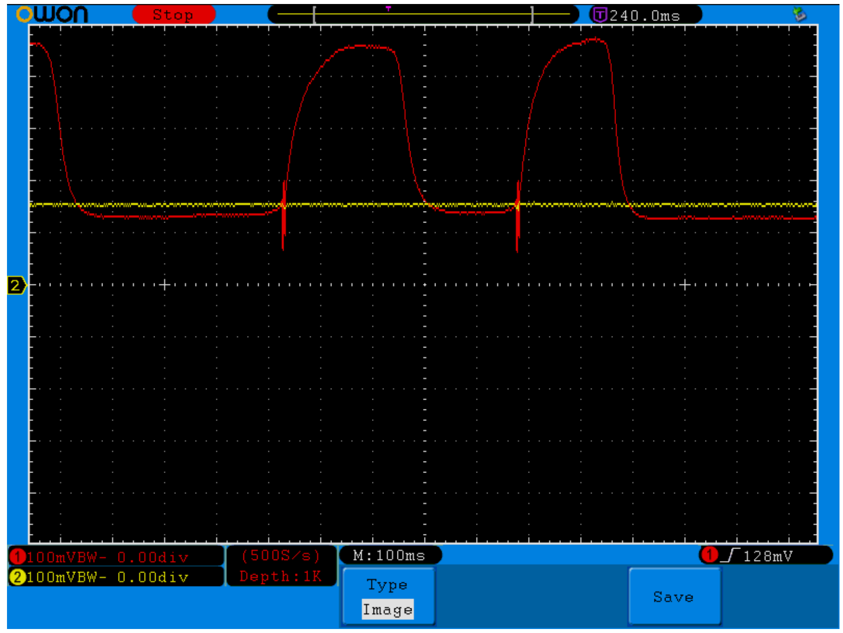


Figure 1-5: Scope images of chatter.

The second image in Figure 1-6 shows how bad it can be when I rapidly move my hand over the sensor quickly.

It turns out that this noise can be handled by adding another resistor to the circuit. This new resistor (R_h) adds hysteresis to the circuit via a feedback loop. A small amount of current is directed from the comparator's output back to the non-inverting (+) input.

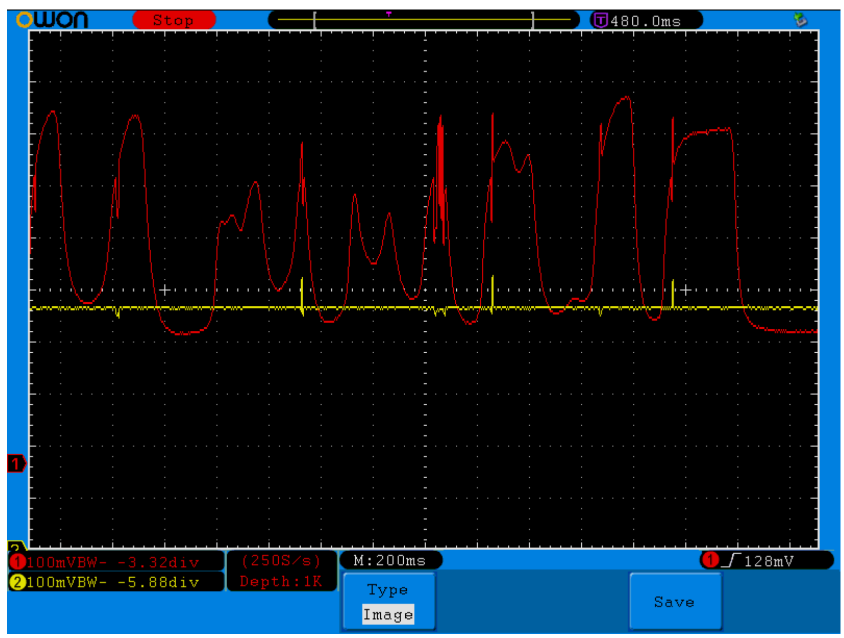


Figure 1-6: Extreme chatter as I move my hand over the LDR and then move away.

"Hysteresis in a circuit arises when an **input above a certain level triggers an output**, but the **output isn't reset until the input reaches a lower level**. With an input between those values, the output remains the same (high or low). The difference between the two input values is the hysteresis." (Stack Exchange).

The following article from Texas Instruments describes the concept in detail:

http://www.ti.com/lit/ug/tidu020a/tidu020a.pdf).

Circuit with Hysteresis:

www.ti.com

A small change to the comparator circuit can be used to add hysteresis. Hysteresis uses two different threshold voltages to avoid the multiple transitions introduced in the previous circuit. The input signal must exceed the upper threshold (VH) to transition low or below the lower threshold (VL) to transition high.

Figure 4 illustrates hysteresis on a comparator. The resistor Rh sets the hysteresis level. When the output is at a logic high (5V), Rh is in parallel with Rx. This drives more current into Ry, raising the threshold voltage (VH) to 2.7V. The input signal will have to drive above VH=2.7V to cause the output to transition to logic low (0V).

When the output is at logic low (0V), Rh is in parallel with Ry. This reduces the current into Ry, reducing the threshold voltage to 2.3V. The input signal will have to drive below VL=2.3V to cause the output to transition to logic high (5V).

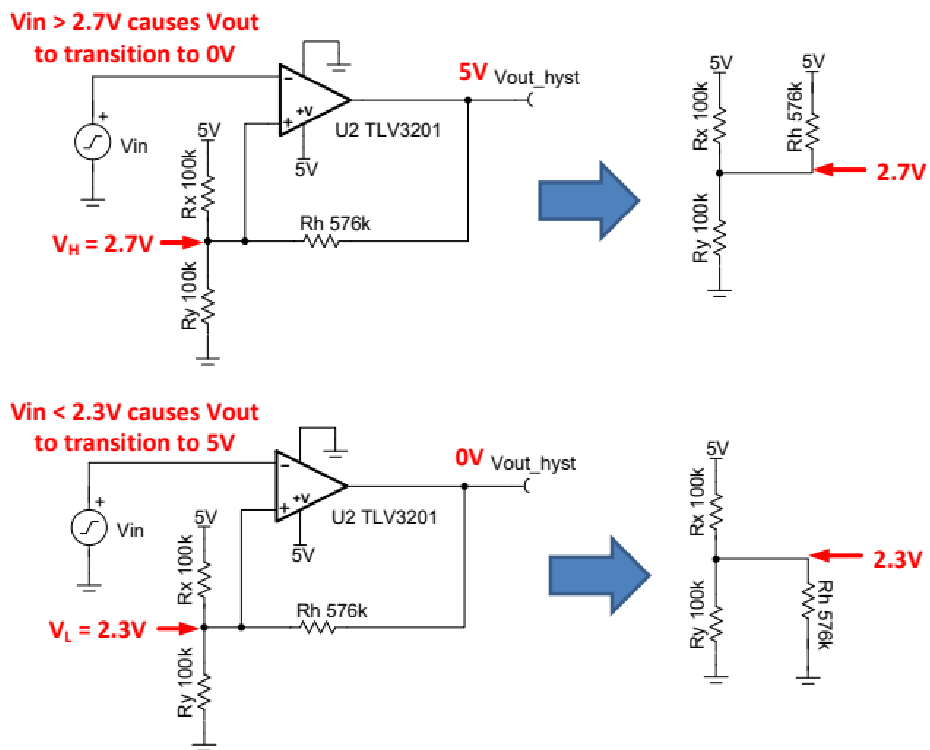


Figure 1-7 Adding a feedback resistor (Rh) adds hysteresis and makes the output steady.

To summarize, let's say my comparator has a reference voltage (non-inverting or + input of 2.5V and Vcc = 5V as shown above. When R_h is added it automatically creates a range for the reference voltage instead of an exact trigger level. In this case, the range is ~2.3 – 2.7V. So, when the output is high (5V) the R_h and R_x are effectively in parallel and thus the resistance is decreased. This causes more current to flow through the R_x /R_y voltage divider and thus raises the reference voltage up to around 2.7. When the output goes low, R_h is in parallel with R_y and sinks more current to ground because of the lower resistance. This lowers the reference voltage to ~2.3V. Any input signal on the (-) pin will not let the comparator change states. To change states, the (-) input must now go higher or lower than these new 2.3 and 2.7 levels. This effectively eliminates this "bouncing" and erratic triggering of the IC. So, the last state the IC was in along with the hysteresis "voltage band" determine when the IC changes state.

Figure 1-8 shows how the noise in a circuit that implements hysteresis responds. Even though there is noise on the input, the first point at which the voltage crosses the threshold causes the IC to "latch" and the noise does not affect the output level.

Figure 5 illustrates the output of a comparator with hysteresis with a noisy input signal. The input must transition above the upper threshold (VH = 2.7V) for the output to transition to logic low (0V). The input must also transition below the lower threshold for the output to transition to logic high (5V). The noise in this example is ignored because of the hysteresis. However, if the noise were larger than the hysteresis range (2.7V – 2.3V) it would generate additional transitions. Thus, the hysteresis range must be wide enough to reject the noise in your application. Section 2.1 provides a method for selecting components to set the thresholds according to your application requirements.

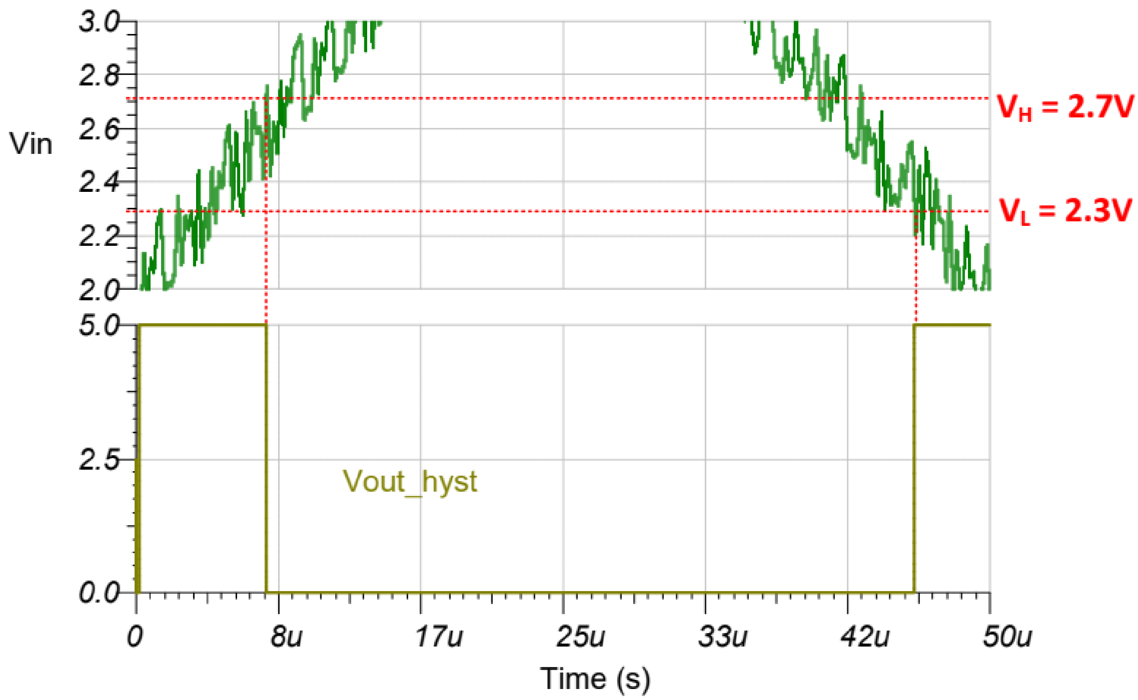


Figure 1-8: Hysteresis changes the thresholds at the inputs of the op-amp and stops the chattering.

How To Design a Hysteresis Circuit

This table shows the formula for computing the value of the hysteresis resistor installed.

2.1 Design of Hysteresis Comparator

Equations (1) and (2) can be used to select the resistors needed to set the hysteresis threshold voltages V_H and V_L. One value (R_x) must be arbitrarily selected. In this example, R_x was set to 100kΩ to minimize current draw. R_h was calculated to be 575kΩ, so the closest standard value 576kΩ was used. The proof for Equations (1) and (2) is given in Appendix A.

$$\frac{R_h}{R_x} = \frac{V_L}{V_H - V_L} = \frac{2.3V}{2.7V - 2.3V} = 5.75 \quad (1)$$

$$\frac{R_y}{R_x} = \frac{V_L}{V_{CC} - V_H} = \frac{2.3V}{5.0V - 2.7V} = 1 \quad (2)$$

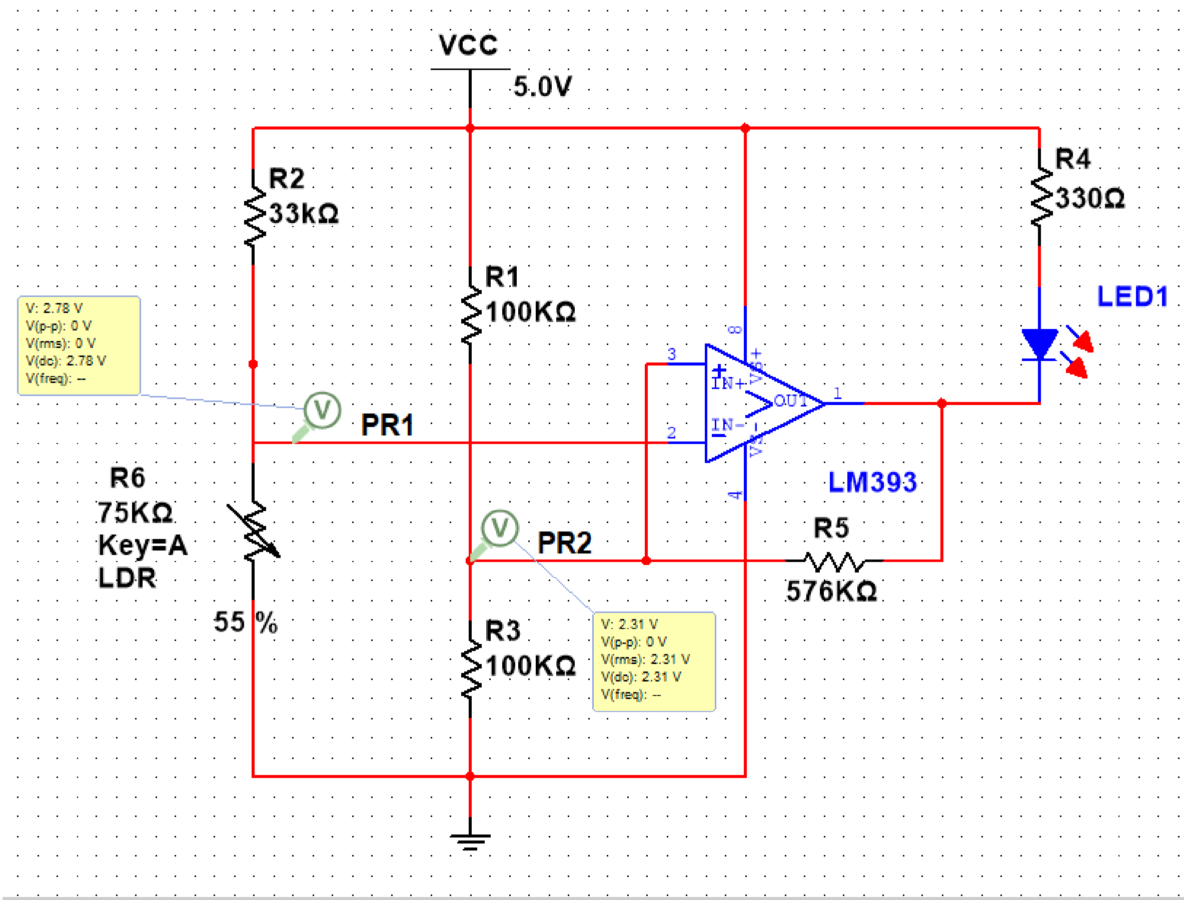
$$R_h = 5.75R_x \quad (3)$$

$$\text{Let } R_x = 100k\Omega \quad (4)$$

$$R_y = R_x = 100k\Omega \quad (5)$$

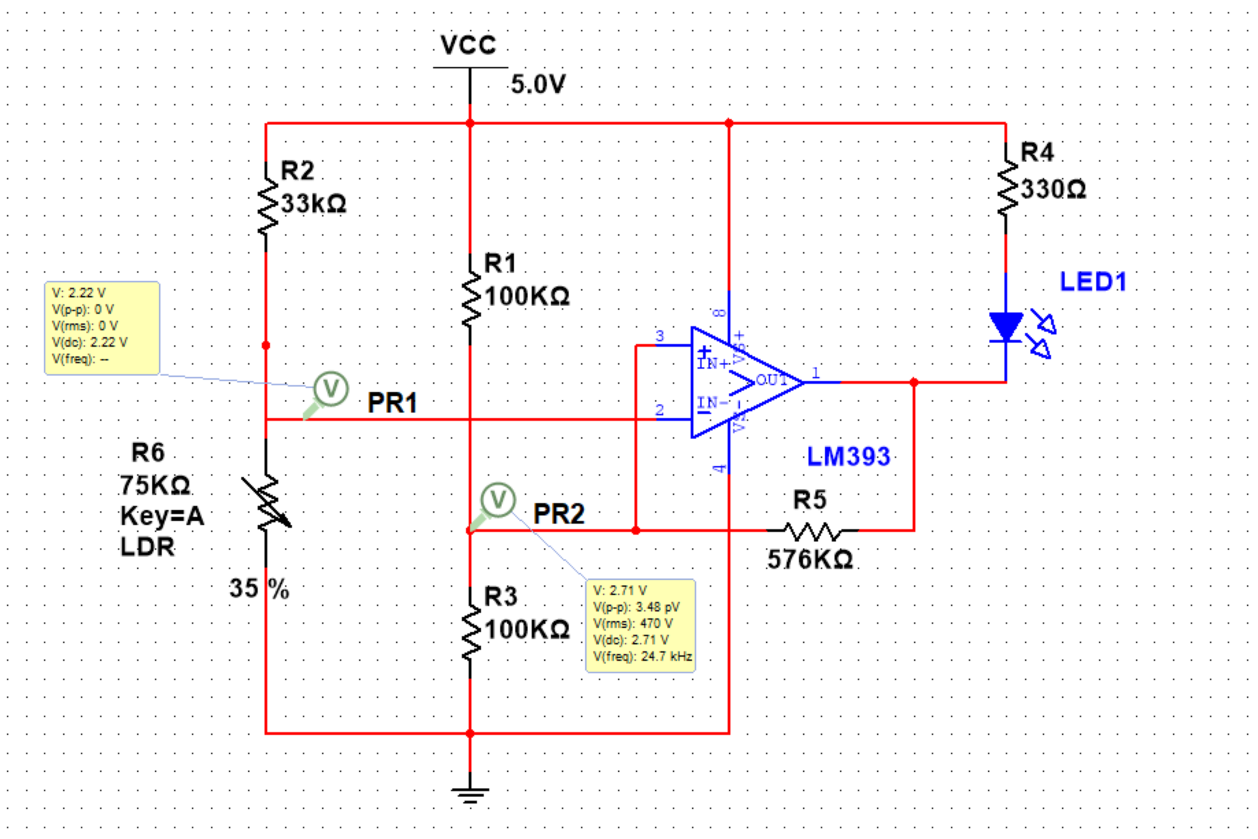
$$R_h = 5.75R_x = 5.75(100k\Omega) = 575k\Omega \quad (6)$$

Here is the completed simulation with hysteresis. Notice that as soon as the voltage from the LDR|R_2 divider > than the threshold, the LED lights up. Also observe the voltage is at the hysteresis level (2.78) at pin 2 and the low hysteresis level at pin 3 is 2.31. These are the calculated values shown on the previous page. The comparator is now "latched" and is waiting for the input voltage to drop below this 2.3 level. Thus, the simulation reflects the actual circuit.



Here the input has been reduced and the comparator has changed to a HIGH state and the LED is off. Once again, the new reference voltage at Pin 3 is set to the upper hysteresis level of 2.7 and is waiting for the input to go below this level in order to change its output state back to LOW.

Together these simulations show the hysteresis effect. New threshold voltages are created by R_5 automatically based on the output state of the comparator.



Light Controlled LM393 Comparator Circuit with Hysteresis

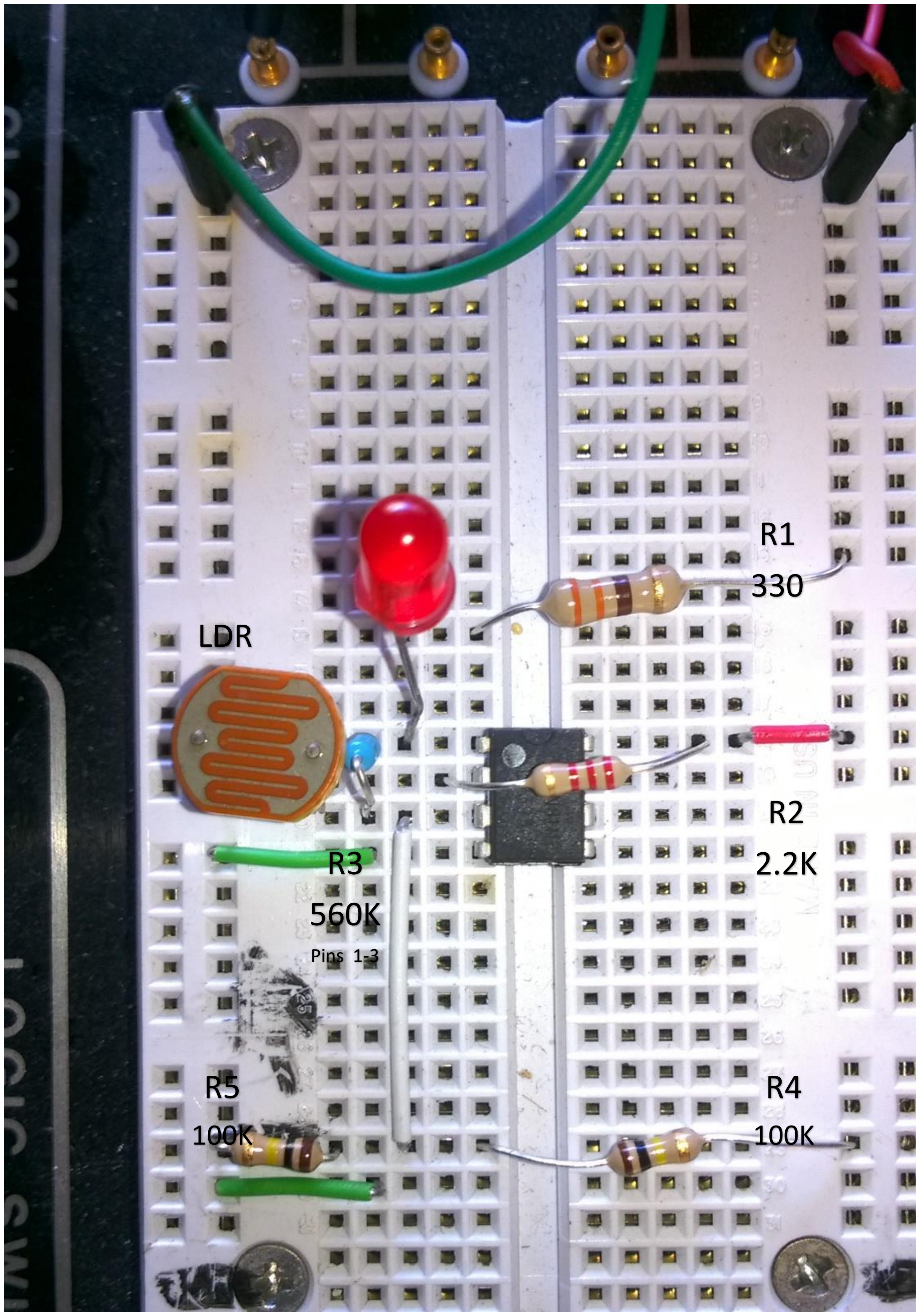
R_1-LED current limiter

R_2-LDR|voltage divider connected to (-) input.

R_3-Hysteresis from output (Pin 1) to Pin 3 (the non-Inverting or + input)

R_4 + R_5 Reference voltage divider on Pin 3 (non-inverting).

Since both resistors are of equal value, the output of the voltage divider = Vcc/2 which is 2.5V in this case.



Now, let's take one last look at our images together for comparison:

Oscilloscope Images of Circuit WITH & WITHOUT Hysteresis

Figure 6 shows the trigger level (yellow) and output of LDR on (-) pin #2. As the LDR changes in resistance, it causes noise much like a switch bouncing. This causes the LM393 to false trigger and the LED to turn on and off erratically.

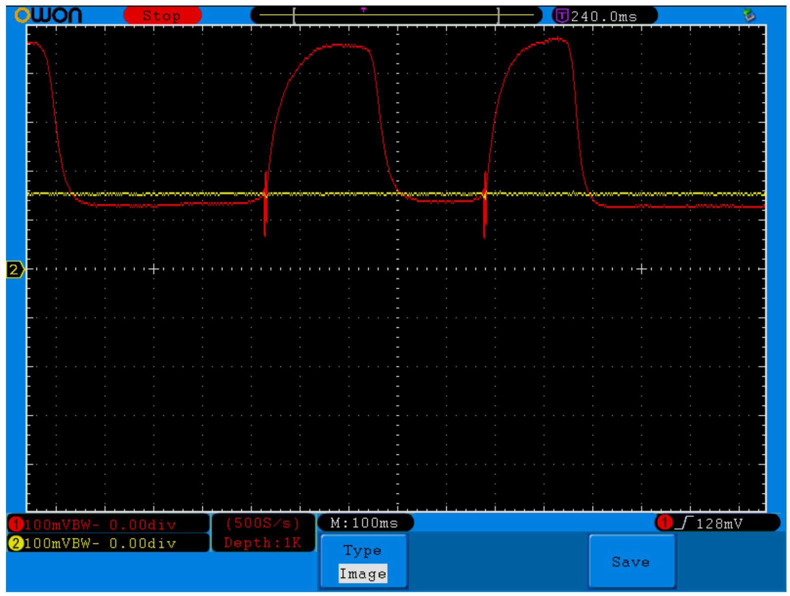


Figure 6 Noise on LDR signal without Hysteresis

In Figure 7 the noise is pronounced as the voltage from the LDR hovers on the (-) input (non-inverting) near the yellow reference voltage which in on the (+) input.

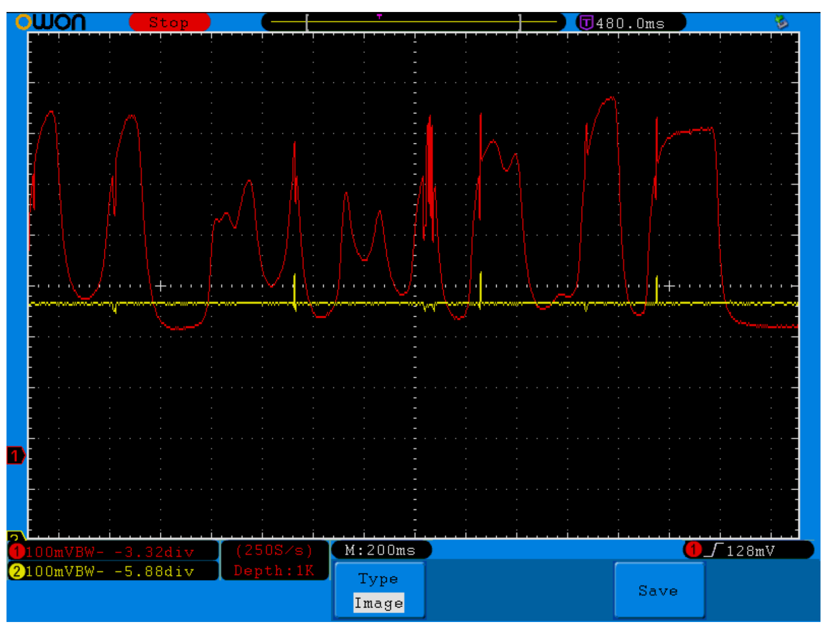


Figure 7 Excessive noise from LDR when signal is near reference voltage

Oscilloscope Images of Circuit WITH Hysteresis Added

Figure 8 shows a clean output from the comparator once hysteresis is added to the circuit. This is accomplished by adding a feedback loop from the output (pin 1) back to the (+) input on the LM393.

The red trace is the input signal from the LDR connected to the inverting (-) input.

The yellow trace shows the output of the comparator. Notice how clean the transitions are.

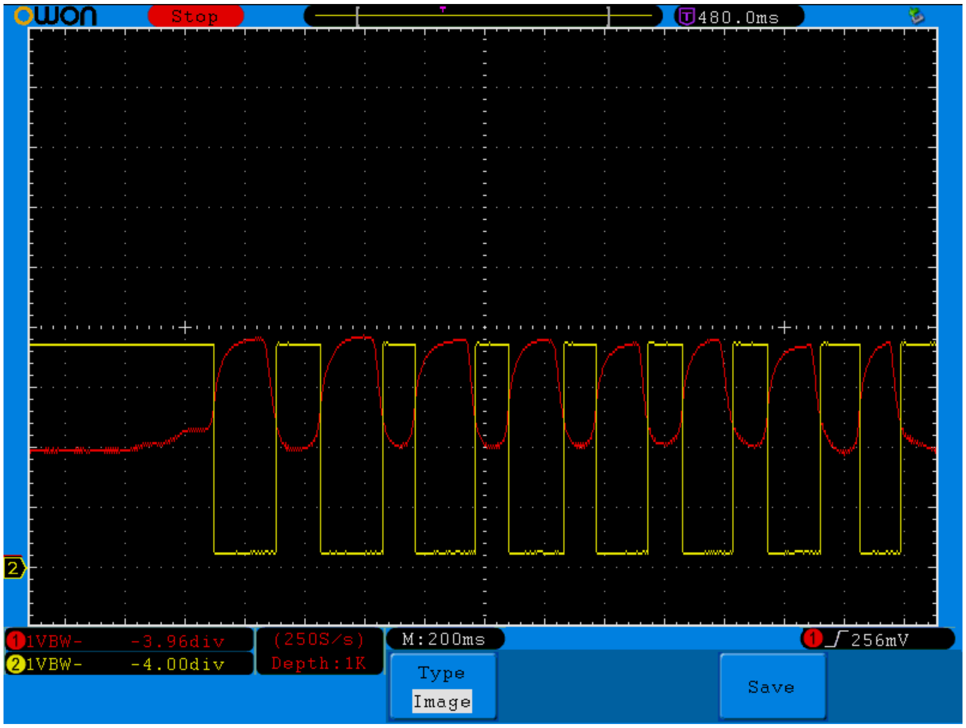


Figure 8 Output Signal (Yellow) and LDR Signal with Hysteresis

Figure 9 shows how the threshold or reference voltage on the non-inverting input (+) is changed by about .2v and this causes the comparator to trigger reliably. Even though the sensor signal can have noise, it is effectively ignored by this configuration.

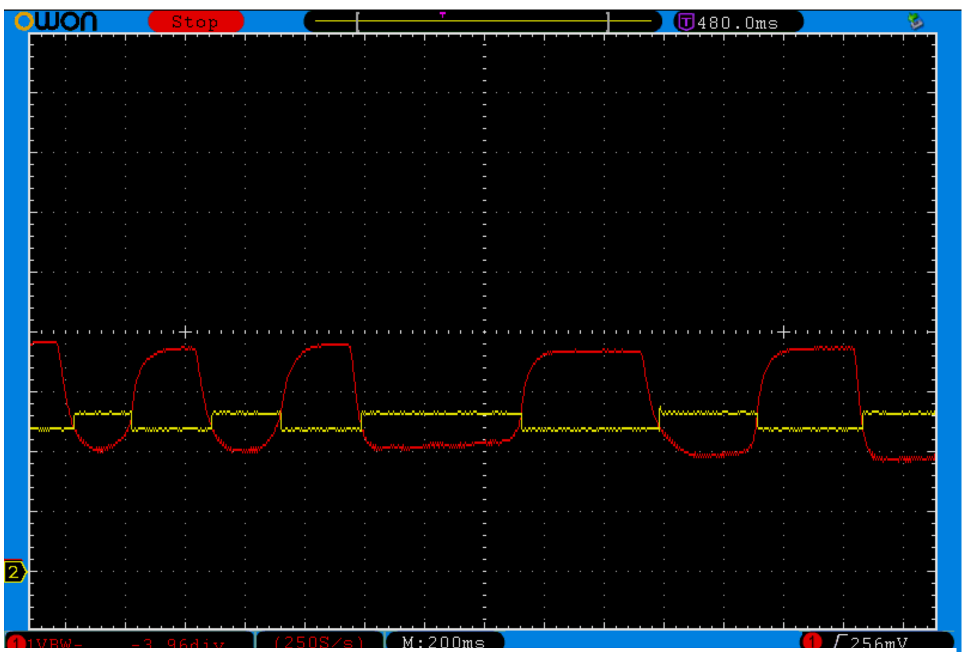


Figure 9 Here the threshold voltage (yellow) is changed slightly by the Hysteresis resistor. Output from the LM393 is fed into the Non-inverting input (+) and stabilizes the output signal. The Led/Load responds in a solid and reliable manner.