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LIGHT SENSOR TECHNOLOGY

measuring daylight using LEDs

Light-sensitive sensors with characteristics similar to those of the human eye are most often implemented using photoresistors or special (and thus expensive) photosensors. Few people realise that normal LEDs can also be used as optical sensors that respond the same as the human eye.

Photodetectors for visible light are most often built using light-dependent resistors (LDRs), which are well-known components. Their spectral sensitivity is similar to that of the human eye. In the SMD age, their 'pros and cons' are their large package sizes, large tolerances, large temperature dependence and large sensor currents, besides which they are expensive and very slow. The speed at which LDRs respond to varying light levels is similar to that of the human eye, with resistance changes occurring in the range of seconds.

Fast photodiodes with sensitivities corresponding to those of the human eye are rare. Most photodiodes are sensitive in the infrared region, extending as far as 1100 nm. The special BPW21 silicon photodiode senses the visible region from 425 to 675 nm and has an active area of 7.5 mm2, and it is packaged in a metal TO5 case. It is considered to be a reference element and priced accordingly, but it is accurate, has excellent linearity and is several orders of magnitude faster than an LDR ($t_{on/off}$ = 6 µs versus $t_{off} \approx$ 3 s). It is often used as a sunlight reference sensor for photovoltaic power systems. The BPW21 phototransistor is classified as a discontinued product, with the Vishay Semiconductors PBPW21R being suggested as a replacement. However, it is still quite readily available. Still, its price is in the same league as that of the Analog Devices AD820 opamp.

Other types of light sensors include modern 'intelligent optosensors' with laboratory characteristics, such as the TAOS TCS230, Agilent Technologies HDSL9000 and Texas Instruments TSL230. There are also components that operate as light-to-frequency converters. The Agilent Technologies type HSMF-C118 is a tricolour RGB LED in an SMD package. A summary of light sensors suitable for use with daylight is given in Table 1.

In the past, a variety of IC manufacturers have attempted to eliminate some of the drawbacks of these sensors and 'trim' them to act as converters with parameters suitable for use in the visible spectrum, with faster response times than passive LDR sensors. For laboratory applications, there are the highly accurate (and thus expensive) Truecolor Dreifeld type MCS3xx RGB colour sensors. They feature standardized spectral sensitivity and colour filtering, and they are planned to be followed by sensor arrays similar to CCD camera chips.

The monolithic OPT301 from Burr-Brown has a relative sensitivity of 80 % for yellow light and a peak response in the near-infrared region. It is only available in the hermetic TO99 metal package. It requires a symmetric supply voltage, which can be a disadvantage for modern applications. In addition, it requires an infrared filter if it is to be used as a daylight sensor.

Daylight

Daylight contains a high proportion of long-wave infrared radiation. We experience sunlight as warm, with the light at sunrise been sensed as cooler than the light at sunset. By contrast, moonlight has a high proportion of short-wave ultraviolet radiation. This is why we experience moonlight as cold. Our brain also 'sees' with our skin, and it's no accident that the spectral composition of light is referred to as its colour temperature. Our eyes have also evolved accordingly, with the result that specific spectral shifts occur according to the intensity of the light, with colour sensitivity decreasing as light intensity decreases.

Incandescent light has a high proportion of infrared radiation, with a negligible amount of ultraviolet. Our eyes cannot sense long-wavelength light (IR or thermal radiation). Our skin cells are better equipped for this task. However, almost all silicon detectors have their peak sensitivities in the infrared region, so they are not suitable for detecting daylight or artificial light.

A normal LED, regardless of its colour, emits visible light, which after all is what it's designed to do. Its efficiency is very low, since most of the energy is converted into heat, although the amount of heat it generates is hardly significant due to its low power dissipation.

In contrast to all other artificial light sources, LEDs emit nearly monochromatic light with high colour saturation. In the CIE chart shown in **Figure 1**, all of the spectral regions for coloured LEDs are located close to the outer edge of the horseshoe-shaped line of maximum colour saturation. At the white point, by contrast, colour saturation approaches zero.

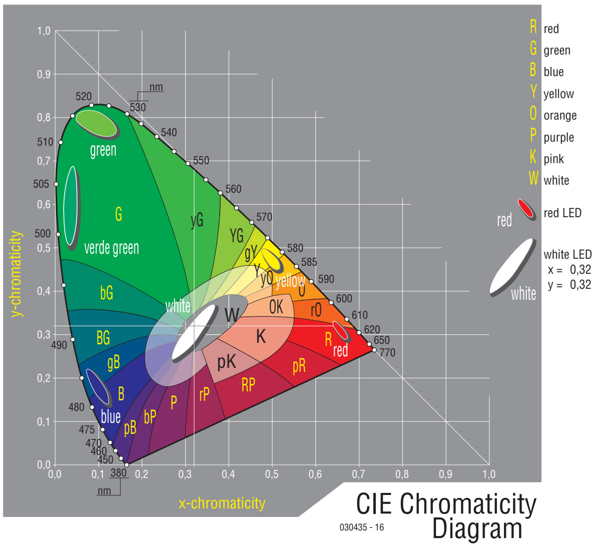

Figure 1. The colour gamut of the CIE standard chart, showing the narrowly demarcated LED regions.

The CIE model

The CIE model is by no means perfect, since it cannot be used to explain colours such as brown or gold. It is thus not suitable for defining or accurately specifying our subjective perception of colour.

Colours outside the range of colour models, such as RGB, CMYK, LAB, and other models, only actually come into existence in our brains. The colour-sensitive cones and rods in our retinas have broadly overlapping spectral responses, which means they all contribute to every image. Their information is transmitted to the brain via chemical impulses in the nerve bundle. On their way to the brain, these impulses are 'premixed' by crosstalk between individual nerve cells, following which they are formed into a colour image in the brain. In this process, the receptors simply transmit impulses lacking any sort of colour information. Colours only come into existence in the brain as the result of combining these impulses and evaluating their mutual relationships.

A 'full-colour' image can be generated using a flat-panel display made from individually driven RGB LEDs. However, the 'spot colours' (colours that cannot be directly generated using the primary colours) are still missing in such a display. On the other hand, the colour saturation of an LED display cannot be matched by any sort of high-quality printing, reflective LC display or CRT monitor, nor even by incandescent lamps with coloured filters. That's why arc lamps are used as light sources for film projectors in cinemas.

All of this demonstrates the virtues and vices of LEDs as colour sensors, taking the human eye as the reference. It is thus hardly surprising that high-quality colour sensors based on LEDs have only recently started to be developed. After all, the evolution of LEDs is still in its infancy, and it can be assumed that there are still many applications waiting to be developed.

Turning things around

Let's simply turn things around: instead of using an LED to emit light, we can place a 'bare' yellow or green LED in a field of light and connect a sensitive voltmeter to its leads. If we do so, we will measure a voltage that varies

Table 1. Integrated daylight sensors

Type	Topology	Sensitivity		Manufacturer	Case
		Range in nm	Maximum in nm		
BPW 21	P-N photodiode	420-675	565	Vishay	TO5 2-pin
OPT 101	Photodiode with OTA	280-1200	850	Burr–Brown	SO8 & DIP8 & SIP5
OPT 301	Photodiode with OTA	200-1150	750	Burr–Brown	TO99 8-pin
TSL 25x	Photodiode with OTA	300-1100	780	Texas Instruments	Plastic 3-pin
MCS3xx	3 RGB P-N photodiodes*	400-510 490-610 590-750	–	Jencolour	TO5 & SO8

* Truecolor Dreifeld RGB colour sensor ICs with dielectric interference filters and standard spectral sensitivity, with or without IR blocker.

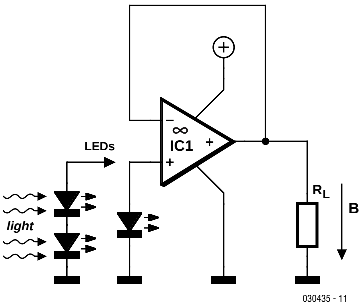

Figure 2. The inputs of a CMOS opamp wired as an impedance converter have such high resistance that they do not place an excessive load on the photovoltaic output of the sensor LEDs.

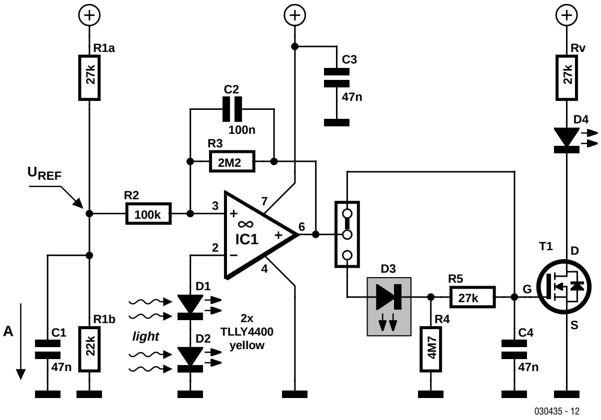

Figure 3. This daylight switch works with almost all types of JFET and CMOS opamps.

according to the intensity of the light falling on the LED.

Unfortunately, these measurements cannot be directly used for anything else, since the extremely small light-sensitive area and low efficiency of the LED mean that this voltage can only be loaded with an extremely small current (in the femtoampère range). Even the internal resistance of a DVM is significantly less than the source resistance of a LED operating in sensor mode.

The circuit diagram in **Figure 2** shows a LED acting as a sensor and connected to the non-inverting input of an opamp. This opamp is wired as an impedance converter and has an input impedance on the order of several teraohms (10^{12} Ω), due to its simple JFET or CMOS inputs. It thus places almost no load on the voltage from the LED sensor. The LED sensor voltages listed in **Table 2** were obtained using this measurement circuit.

Here the designation 'impedance converter' is actually not entirely correct, since this is a transimpedance amplifier, which is a two-port network characterised by current, voltage and impedance conversion. In the circuit shown in Figure 2, the transimpedance amplifier is only wired as an impedance converter. However, this does not need to be discussed any further here.

Figure 3 shows an electronic switch that switches on the connected load RL at dusk and switches it off again at dawn. The network formed by R1–R3 provides a reference voltage UREF = 2.25 V at the non-inverting input, with a measured hysteresis of approximately 250 mV. This threshold value is not critical; it is suitable for two low-current yellow LEDs connected in series.

With two LED sensors oriented in different directions, the threshold level is crossed relatively quickly during twilight. Resistors with ten-percent tolerance are adequate for this 'precision' circuit. Using two LEDs makes the circuit insensitive to artificial light falling on only one sensor, such as light from a streetlight or car headlights. The 'lag circuit' consisting of LED D3, R4, R5 and C4 also helps here. D3 is enclosed in a length of heat-shrink tubing, which gives it significantly better blocking characteristics than a regular diode.

Opamp selection

In theory, a TLC271 (which has a single p-channel MOSFET input stage) is a suitable choice, since its input bias current is just as low as that of the AD820. In practice, however, it is inclined to oscillate at the switching point. This tendency to oscillate also cannot be eliminated with the TLC271, OPA132, AD8035, AD8510 and TLE2081 opamps. With an AD8065, AD820 or AD8610, a network composed of R2, R3 and C2 can be used to generate a hysteresis, which is necessary to provide jitter-free switching with 'creeping' twilight. The lag circuit is not necessary with the latter types of opamps.

A TL081 does not see the integration network as the source of a threshold potential, but only as a feedback network that sets the gain. In a circuit built according to Figure 2, a Schmitt-trigger circuit should thus be placed between the output of IC1 and LED D3. In any case, the TL081 does not oscillate all that wildly.

The high-precision OPA665 is fully overqualified (and correspondingly expensive) for the job of daylight sensing. It can be used to build a fast detector for arc lamps. However, it is designed to operate from a bipolar ±5 V supply.

The photo at the head of the article shows a prototyping board (EVM) from Texas Instruments that the author used to test the various types of opamps in the daylight sensor circuit. **Table 3** provides a summary of suitable operational amplifiers. Other types of opamps having bipolar input transistors or complementary MOSFETs are unsuitable, either because their input resistance is too low or because their input offset current is much too high. Such offset currents result from always-present differences in the gate currents of the complementary transistors in the input stage.

The switching point can be shifted to accommodate other light intensities or other types of LEDs by adjusting the values of R1a and R1b. When adjusting these values, it is best to short out the time-delay network (D3, R4 and R5). This time-delay network is a lag circuit with a switch-off delay of approximately 3 s. This may appear to be relatively short compared with the duration of twilight at our latitudes, but it is based on practical experience. Just bear in mind that for colour vision, our eyes have a dynamic range for light intensity of around 100 dB (from approximately 0.1 lux to 20,000 lux).

During twilight, the voltage across the LEDs increases or decreases markedly. It thus passes through the switching-point hysteresis band relatively quickly. For extremely slow changes in light intensity, a modern operational amplifier such as the AD8610 should be used, since it has practically stable switching behaviour and a small amount of light hysteresis. This may make it possible to omit the time delay circuit.

Table 2. Equivalent LED voltage for mean morning/evening twilight levels and a moonless night (Figure 1 output)

LED	Type	U_{BIAS} [V] with one LED		U_{BIAS} [V] with LEDs	
		Twilight	Dark	Twilight	Dark
Yellow	TLLY4400 (3 mm low-current)	1.1	0.8	2.2	1.0
Red	TLLR4400 (3 mm low-current)	1.0	– [1]	2.0	– [1]
Green	TLLG4400 (3 mm low-current)	1.2	0.8	2.4	1.4
Blue [3]	LF-59EBGBC (5 mm RGB)	1.5	– [2]	2.4	– [2]

1: A red LED detects near-infrared radiation, so it cannot be used to measure night-time light.
2: Not measured.
3: Only one blue LED connected.

Table 3. A selection of suitable opamps with JFET input stages

Type	GBP in MHz	Offset in μV	Input bias in pA	U_{CC} in V	I_{CC} in mA	U_{IN} max. in V	Manu-facturer	Case	Tested?	Note(s)
AD8033	80	1000	1.5	+5 to 24	3.3	0 to $+U_{CC}-3$	Analog Dev.	SO 8 & SOT 23	yes	Shutdown
AD8065	145	400	2	+5 to 24	6.4	0 to $+U_{CC}-3$	Analog Dev.	SOT 23	yes	
AD820	1.8	100	2	+3 to 36	0.65	-0.2 to $+U_{CC}-1$	Analog Dev.	SO 8 & DIP 8	yes	
AD8610	25	85	2	+5 to 26	3.5	0 to $+U_{CC}-3$	Analog Dev.	SO 8 & MSOP8	yes	
AD8627	5	500	0.5	+5 to 26	0.75	0 to $+U_{CC}-1$	Analog Dev.	SO 8 & SC70	yes	
OPA132	8	250	5	+5 to 36	4	Rail-to-Rail (input and output)	Burr–Brown	SO 8 & DIP 8	yes	THD = 0.000.08%
TLE2071	10	500	6	+4.5 to 36	1.7	0 to $+U_{CC}$	Texas Instr.	SO 8 & DIP 8	yes	Offset adj.
TLE2081	10	1100	6	+4.5 to 36	1.7	0 to $+U_{CC}$	Texas Instr.	SO 8 & DIP 8	yes	Offset adj.
TL081C	3	3000	5	+4.5 to 16	1.4	0 to $+U_{CC}$	Texas Instr.	SO 8 & DIP 8	yes	Offset adj.
TLC271C	0.09	1100	0.1	+3 to 16	1	-0.2 to +UCC-1	Texas Instr.	SO 8 & DIP 8	yes	Offset adj.
OPA655	240	1000	-5	±4.75 to 5.25	25	±2.75	Burr–Brown	SO 8 & DIP 8	no	
INA121	–	200	4	±2.25 to 18	0.45	$-U_{CC}+2$ to $+U_{CC}-1$	Burr–Brown	SO 8 & DIP 8	no	Precision InAmp

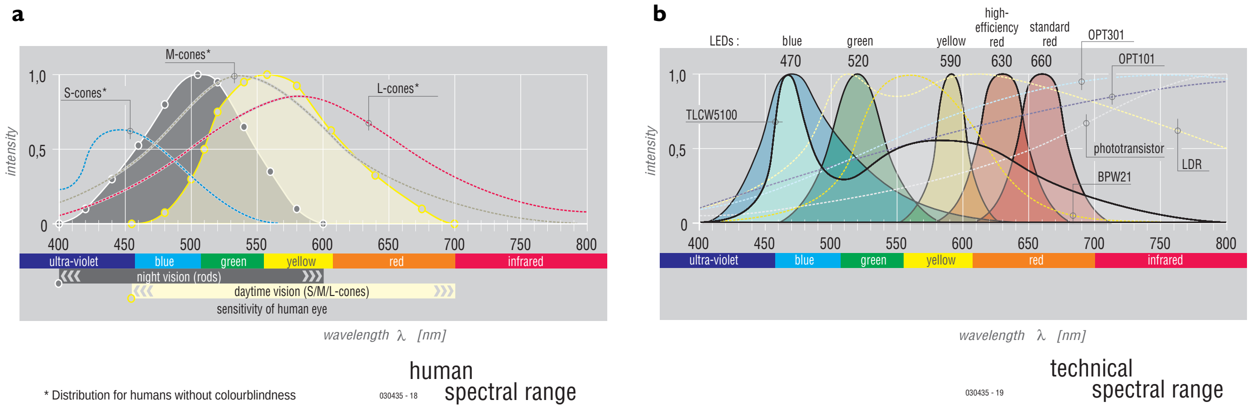

Figure 4. Comparison of human spectral ranges (a) and technological spectral ranges (b).

Light spectra and human vision

Figure 4 shows the daytime and night-time light sensitivities of the human eye, along with the spectra of a variety of electronic components. The spectral sensitivity of the eye changes with differing lighting levels. This is reasonable, since we can see not only bluish moonlight, whose spectrum is close to the UV region, but also yellowish sunlight, which is shifted toward the IR region.

Just as the retina adapts to different brightness levels, it also adapts to colours if they are observed for relatively long times. We sense a white sheet of paper as white, even if it is being illuminated by incandescent light, because our memory tells us the paper is white, although it is actually reflecting yellowish-red light.

Our eyes can also adjust to an enormous dynamic range of brightness, ranging from night vision to day vision. This is a range of 0.00001 to 1,000,000 cd/m^2, which corresponds to a dynamic range of 220 dB. No artificial component can achieve this dynamic range. Perception of colour and contrast improves with increasing light intensity, but decreases again with very bright light. However, in the majority of this range of light intensity our eyes are predominantly sensitive in the black-and-white spectrum. In the colour region, our eyes have a dynamic range of 'only' 100 dB.

The human sense of colour is individual. There is no such thing as a green that is perceived the same by everybody, a neutral grey that is the same for everyone or a perfect white. All monitor calibrations are based on the subjective colour perception of the user in question. By contrast, it is certainly possible to standardise radiant sources relative to each other, such as the grey of a cloudy afternoon, the white of an incandescent lamp or the Sahara yellow of a car body, because they are technically measurable, adjustable and repeatable.

The retina, which covers the inside of the rear hemisphere of the eyeball, consists of a network of cone-shaped and rod-shaped sensor cells (receptors) that convert incident light into electrochemical substances (neuronal energy). The arrangement and relative numerical distribution of these receptors varies over the entire rear hemisphere of the eyeball. These factors vary relative to location on the surface of the retina, and they also vary from one person to the next.

Approximately 100 million rods are active for night vision, and approximately six million cones are active for day vision. Just as multicoloured LEDs have narrow bandwidths and different radiation intensities, the sensory cells for brightness, contrast and colour have complex, differentiated sensitivities, but they have relatively large bandwidths. There are three types of cones, which are sensitive to daylight. They respond to short-wavelength, medium-wavelength and long-wavelength light and are thus called S, M and L cones, respectively. In contrast to the nearly monochromatic colour emission characteristics of LEDs, the cones have broadly overlapping response curves.

Colours in the blue region appear to be darker than colours in the green and red regions because the short-wavelength sensor cells respond more weakly to stimuli. Due to the large overlap in the spectral sensitivities of the S, M and L cones, a person with 'normal' vision has especially high spectral sensitivity at 555 nm (green) for day vision (photopic vision). The BPW light sensor is matched to this peak sensitivity, as are light signalling systems used for railways and marine transport. By contrast, modern traffic-light systems now take people with non-standard colour perception into account and emit green signal light with a large blue component.

The lenses of our eyes absorb ultraviolet light. People who develop cataracts can have the natural corneal lens replaced by an artificial plastic lens. Such people can then see UV light in a range extending to below 300 nm, thanks to their S cones. Insects are especially sensitive to UV light. For people with normal vision, the maximum spectral sensitivity for night vision (skoptic vision) is at 507 nm.

During data transmission from the sensory cells to the brain, there is crosstalk between neighbouring cell groups, not only in the retina but also in the optic nerves and in the brain. A virtual image only comes into existence after these nerve impulses arrive in the brain, where they are processed with reference to information already stored in the brain and converted into an image. The eye is only the measurement sensor for this process, and the actual sensory cells are 'blind' to colours and shapes. They simply convert light energy into electrochemical stimuli, which contain neither colour data nor image data. This is comparable to a graphic processor card with its three RGB lines to a monitor. Here only voltages are transmitted, not colour data or image data.

In a certain sense, the eye digitally decomposes the photorealistic image impinging on the individual receptor cells via the pupil and lens. Due to the crosstalk between neighbouring receptors, optical nerves and brain cells, what we see is again a non-pixelated, photorealistic image without any sort of rasterization, moiré effects or colour fringes (such as are generated by a monitor and are well known in printing technology, since monitors and paper simply don't have brains). This means that a colour stimulus in the brain only arises from combining the information from all of the receptors and optic nerves.

> *Colour is not in the light and not in the eye, but in the brain.*
>
> Isaac Newton

These complex chemical and electrical conversions and transfers make standardisation impossible, especially because the levels of endogenous substances in the body can change colour perception. This occurs with vitamin deficiencies or with emissions of endogenous substances, which in extreme cases can lead to a blackout, in which the brain sees white increasingly strongly, colours become increasingly washed out and grey tones become brighter. (Of course, here we're not referring to the blackouts of certain well-known politicians!)

However, colour by itself is not a predominant consideration in the brain. This becomes evident if we attempt (in vain) to determine the distance to a light source. We may know the distance to a star in the night sky, but we estimate the distance to a lamp using its surroundings. Consequently, the brain needs to know not only the colour emission characteristics of an object, but also its structure and the nature of its surface (relative to stored experience), in order to generate an image using the total colour information. In the overall process, the brain also evaluates other impulses, such as may come from the senses of touch, taste, smell and hearing — and from the second eye.

Approximately 8–10 percent of all European men and 0.5–1 percent of European women have hereditary reduced sensitivity to red and/or green. The normal ratio of the sensitivities of the three photoptic S, M and L cones is 10 % blue, 48 % green and 42 % red. With a chromatic visual deficiency, the three types of cones have a different relative distribution (such as a green deficiency with a distribution of 30 % blue, 30 % green and 40 % red). Some colour-blind people can still properly distinguish green from red, others do not see any difference between red and green, and yet others have a chromatic deficiency only in the central, acute vision region of the eye.

The cone distribution differs from person to person, and it also varies over the total surface of the retina. Red/green differentiation decreases steadily with increasing distance from the central acute vision region (toward the outer edge of the hemispheric rear surface of the eye).

Total colour blindness is very rare and occurs in only 0.003 percent of the population. There is also a yellow/blue form of colour blindness. Colour blindness is a hereditary deficiency that does not change with age, and it cannot arise during the course of a person's life, since it is inherited.

The 'normal' red/green distribution is relative to Central Europe and originates from the ancient times of hunters and gatherers, when it was vital to survival to be able to gather red berries from beneath green leaves or follow blood traces in the forest. Strictly speaking, our normal condition amounts to a hypersensitivity for red/green contrast perception, which is not necessary in other types of landscape such as deserts or polar regions. Colour blindness as a visual deficiency is thus relative to the visual capacity of a majority of the population in a particular landscape.

For persons in professions such as web design and equipment design, who deal with the visual aspects of devices, it is certainly important to pay attention to this phenomenon, since men and women with various forms of colour blindness form a considerable proportion of our population. What is white? What is blue? What is a neutral grey? These considerations influence phenomena such as simultaneous contrast (apparent colour tinting of an area seen against a background), colour stereoscopy (which causes red to appear to be closer and blue further away), illegibility of red text on a green background, and other types of chromatic displacement. After all, our lives and our moods depend on colour.

The technology used in our electronic media is similar to the biology of our eyes. However, no-one has yet succeeded in using technical resources to transform the information from our nerves and brain into a photograph.

Summary

Light sensors using standard LEDs as sensors connected to opamps with JFET inputs or simple MOSFET input stages are certainly worth consideration. In such a configuration, various types of IC topologies exhibit different types of oscillatory behaviour during switching.

With relatively old types of ICs, the frequency of oscillation at the switching point can only be defined with integrating feedback using C2 and R3. By contrast, with more recent types of opamps an RC network at the non-inverting input produces better-defined switching behaviour with additional hysteresis over the range of light intensity. This depends on the integrated compensation system of the IC, which is not externally visible.

For a simple light sensor built according to Figure 2 and having a time delay of 3 seconds, all of the listed types of opamps are suitable. Their mutual differences are essentially smaller than the variations due to the passive external components. Altogether, this yields an accurate, economical SMD design using fewer components and having a smaller area than with a discrete BF245 JFET, a standard opamp and a trimpot.

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