APPLICATION NOTE

ANO014 | Signal transmission using IR diodes and photodetectors

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1. INTRODUCTION AND THEORETICAL BACKGROUND

In signal transmission, the combination of an infrared diode (IR LED) and a photodetector has become indispensable, offering simple and versatile wireless data transmission. The applications are not limited to industrial settings – infrared communication is relevant in everyday life, for example in remote controls, medical devices, motion detectors, and security systems. To use these components correctly, it is important to understand how the IR diode and photodetector "team" behaves in applications. This application note therefore focuses on the behavior of phototransistors and photodiodes under different circuit conditions. To this end, the effects on collector current or photocurrent, output voltage, and, in the case of phototransistors, switching times, are analyzed.

First, a brief introduction explains how the IR LED and the phototransistor or photodiode behave on their own, then to understand what must be considered when combining the "emitter", the IR LED, with the "detector", the phototransistor or photodiode.

1.1 IR-LED as emitter

Physical parameters in the datasheet

- Peak wavelength - λ_{PEAK}: Wavelength at which the most light is emitted
- Centroid wavelength - $\lambda_{CENTROID}$: Peak wavelength of the spectrum
- Radiant intensity - I_e: Radiated power per solid angle in a specific direction (W/sr)
- Forward voltage - V_F: Voltage across the LED in forward operation
- Spectral bandwidth – $\Delta\lambda$: Bandwidth of the wavelength spectrum with an intensity of at least 50% of the maximum
- Viewing angle - $2\Theta_{50\%}$): Angle at which the IR LED emits

Like any diode, the IR LED has an I-V characteristic curve (see Figure 1).

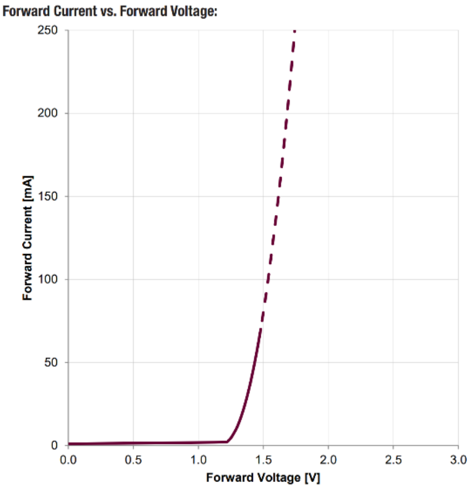

Figure 1: Example of the forward current profile I_f against the forward voltage V_f of the IR-LED.

This provides a clear characterization and describes the current-voltage behavior of the IR LED in forward direction.

For data transmission, however, the optical properties are crucial, especially the IR emission at a given current. The key parameter for IR LEDs is radiant intensity.

For Würth Elektronik's IR LEDs, the relationship between radiant intensity and forward current is approximately linear (see Figure 2).

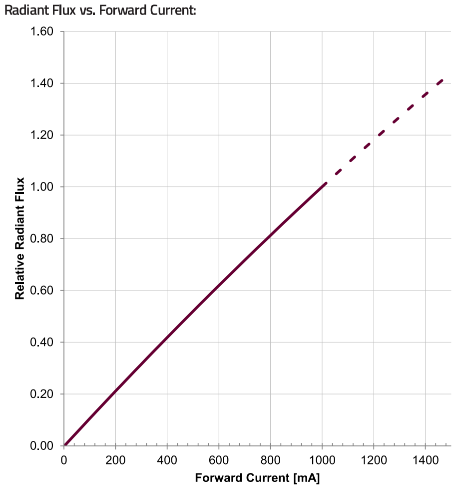

Figure 2: Example of the radiant intensity profile against the forward current of the IR LED.

This allows the electrical and optical behavior to be characterized almost completely.

However, additional parameters are of critical importance for data transmission. The wavelength (850 nm or 940 nm for WE) and the emitted spectrum are particularly important and both must be considered. These parameters must be matched to the detector, which will be shown later. In relation with radiant intensity, as previously described, the angle in which the LED emits plays an important role. When selecting a suitable IR LED, these datasheet values must be adapted to the specific application and conditions.

For data transmission, the IR LED is operated in pulsed mode. This has the advantage that less energy is required and the signal can be digitized more easily than in continuous mode. To ensure only minimal delays on the emitter side, it is important to pay attention to the IR LED switching times. As can be seen in Figure 3, IR LEDs have relatively long rise and fall times at low currents; these decrease significantly as the current increases.

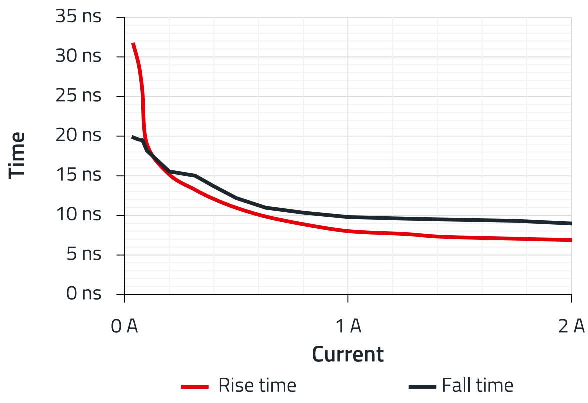

Figure 3: Example of the switching time profile of IR LEDs.

The exact dependence on current and the magnitude of the switching times vary from one LED to the next and must be evaluated individually for each application.

1.2 Phototransistor and photodiode as detectors

Once the optical signal has been transmitted by the IR LED on the emitter side, it must then be converted back into an electrical signal on the detector side. Würth Elektronik offers two options here: The phototransistor and the photodiode. In both components, the input parameter is infrared light, and the output parameter is a current: photocurrent for photodiodes and collector current for phototransistors.

Physical parameters in the phototransistor datasheet

- Wavelength of peak sensitivity - λ_{PEAK}: Wavelength at which the phototransistor's sensitivity is at its maximum
- Range of spectral bandwidth - λ: Wavelength bandwidth to which the phototransistor is sensitive
- Collector current - $I_{CE,P}$: Current flowing through the phototransistor (approximation $I_E \approx I_C$)
- Collector-emitter dark current - $I_{CE,DARK}$: Collector current that flows without illumination of the phototransistor
- Viewing angle - $2\Theta_{50\%}$: Angle at which the phototransistor detects

Physical parameters in the photodiode datasheet

- Wavelength of peak sensitivity - λ_{PEAK}: Wavelength at which the photodiode's sensitivity is at its maximum
- Range of spectral bandwidth - λ: Wavelength bandwidth to which the photodiode is sensitive
- Photo current - I_P: Current flowing through the photodiode
- Dark current - I_D: Photocurrent that flows without illumination of the photodiode
- Viewing angle - $2\Theta_{50\%}$: Angle at which the photodiode detects

These detectors are available from the WE portfolio in various packages with wavelengths of 850 nm and 940 nm. The relationship shown in Figure 4 between irradiance and photocurrent or collector current is linear for both.

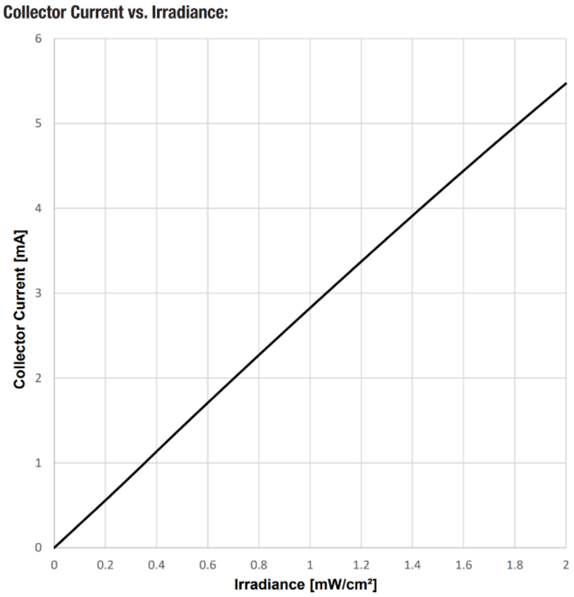

Figure 4: Typical profile of the current against irradiance.

The main differences between the photodiode and phototransistor are in the switching time and the current.

The switching times of phototransistors are in the microsecond range, whereas photodiodes operate in the nanosecond range. The photocurrent is only a few microamperes, while the collector current is in the order of milliamperes. Depending on the application, it must be determined which detector makes more sense. This application note focuses on the behavior of both components under different circuit parameters.

There are generally two basic circuit models for the two detectors. For the phototransistor, these are the common collector (CC) and common emitter (CE) circuits (Figure 5):

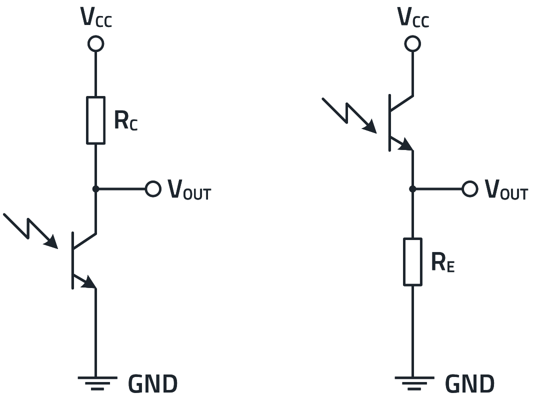

Figure 5: Circuit models for the photodetector (CC circuit on the left, CE on the right).

With increasing irradiance, the output voltage decreases in an emitter circuit, while it increases in a collector circuit. The same circuit models can be applied to the photodiode. The output voltage can be calculated from Ohm's law. For the collector circuit, this means (1):

$$V_{OUT} = V_{CC} - R_L \cdot I_{CE/P} \qquad (1)$$

And for the emitter circuit:

$$V_{OUT} = R_L \cdot I_{CE/P} \qquad (2)$$

The most important parameters for both the phototransistor and the photodiode are listed in the datasheet. The key electrical parameter is the collector current or photocurrent, which is specified as a function of irradiance. There is a linear relationship for both detectors, as was shown in Figure 4. For the phototransistor, the collector-emitter voltage (the applied supply voltage) also plays a role: as the collector-emitter voltage increases, so does the collector current, as shown in Figure 6.

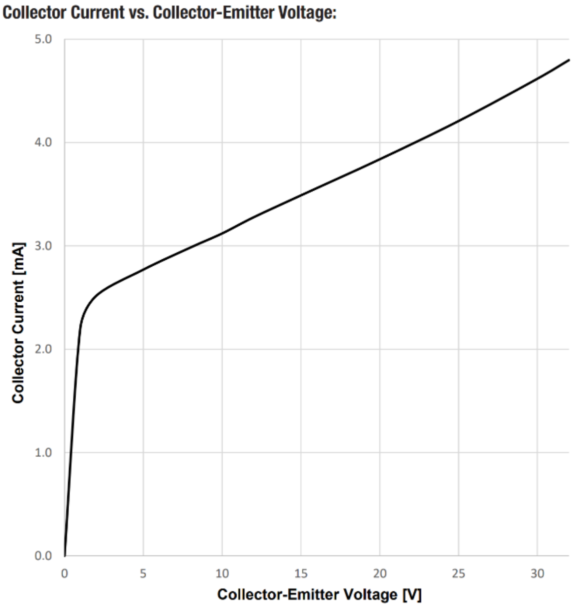

Figure 6: Collector current against collector-emitter voltage.

These two graphs almost completely characterize the electro-optical coupling.

As with the IR LED, additional optical parameters are important for the photodetector. These include the wavelength of maximum sensitivity and the bandwidth of the phototransistor, which should be matched to the IR LED. The viewing angle is crucial, as it indicates the angular range within which the photodetector can detect. These parameters are specified in the datasheet, as described above.

When considering the bandwidth of the detector, it is advisable to check whether a daylight filter should be used. This filters visible light, thereby reducing interference from external light sources.

1.3 Infrared Dream Team – a combination of emitter and detector

The advertising slogan "Infrared Dream Team" describes the perfectly matched combination of emitter and detector from Würth Elektronik. This ensures optimal communication efficiency between the emitter and detector. In turn, this enables fast switching times and perfect coupling between the IR LED and photodetector.

To make this work, the sensitivity of the photodetector is matched to the emission spectrum of the IR LEDs – see Figure 7.

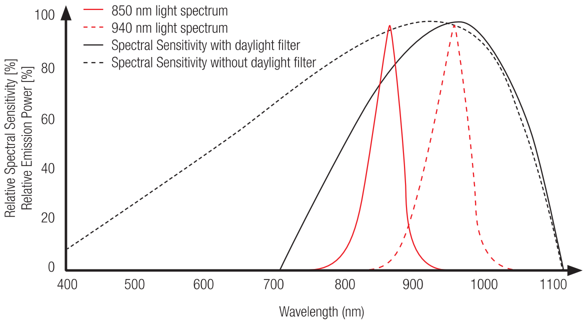

Figure 7: Relative sensitivity of the phototransistor/photodiode and the relative emission power of the IR LED against wavelength.

1.4 Switching times of the components

The switching time describes the delay in the switch-on or switch-off process of an electronic component. The entire duration of the switching process can be shown by applying a rectangular pulse. For using an IR emitter and a detector, the profile of the signal applied to the IR LED is compared with the signal at the detector's load resistor. Figure 8 shows the relationship between the switching times.

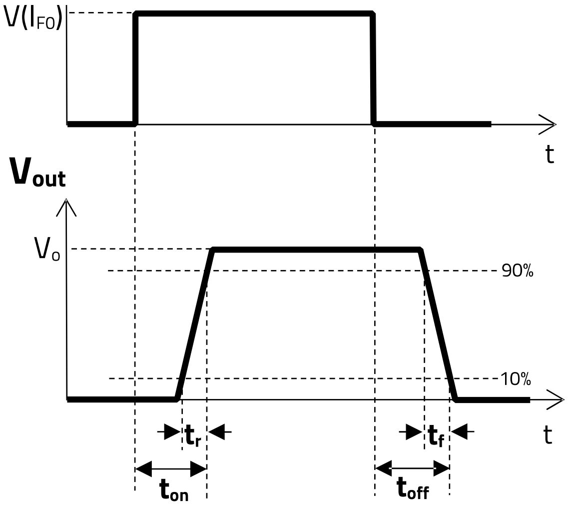

Figure 8: Switching times of the input and output signal.

The time offset between the voltage applied to the IR diode and the voltage measured at the phototransistor load resistor includes both the delay of the IR diode current and the delay of the phototransistor collector current, depending on the incident light.

The total delay from the rising edge of the input signal (shown idealized in Figure 8) to 10% of the output signal is known as the delay time $t_{D,\,ON}$. The time the output signal takes to rise from 10% to 90% of its value is known as the rise time t_r. The sum of these two times is referred to as the switch-on time t_{ON}. Conversely, the time from the falling edge of the input signal to 90% of the maximum value of the output signal is the switch-off delay $t_{D,\,OFF}$. The interval from 90% to 10% of the output signal is known as the fall time t_f. Here, the sum of the two is referred to as the switch-off time t_{OFF}. The following section considers how the rise and fall times relate to the various circuit parameters.

The delay of the input signal at the IR LED to the phototransistor is in the nanosecond range and thus significantly shorter than the switching time of the phototransistor, which is in the microsecond range, so it is negligible in practice.

The following equation can be used to describe the switching times of the phototransistor.[1]

$$t = \beta_0 \cdot \left(\frac{k \cdot T}{q \cdot I_{CE}} \cdot (C_{EB} + C_{CB}) + R_L \cdot C_{CB} \right) \qquad (3)$$

β_0: photocurrent amplification
k·T: Boltzmann constant multiplied by temperature
q: elementary charge
I_{CE}: collector current
C_{CB}: capacitance between collector and base
C_{CE}: capacitance between collector and emitter

As evident from equation (3), the switching time depends on the parasitic capacitances of the phototransistor. From the analogy with a capacitor, it is known that it requires a certain time to charge and discharge. As in this case, this leads to delays in the rise and fall time of the voltage.

The switching times for the photodiode are not considered separately in this application note, as they are in the range of under 100 ns (as previously mentioned). In general, the relationships described for the phototransistor can be applied to the photodiode.

2. CIRCUIT SETUP FOR ANALYSIS

Various circuits with transistors, OP amps, etc. can be used in real applications on both the emitter and detector sides. However, the focus of this application note is to illustrate the behavior of the components, which is why a simple circuit was chosen. This makes it possible to explain the fundamental properties of the components and to transfer their behavior to more complex circuits. On the emitter side, a pulse generator is connected in series with a current-limiting resistor R_f and an IR-LED. On the detector side there is a similar setup which uses an emitter circuit. Here, a supply voltage V_{CC} is applied to a series circuit consisting of a phototransistor/photodiode and a load resistor R_L. The complete circuit diagram used for the following results is shown in Figure 9.

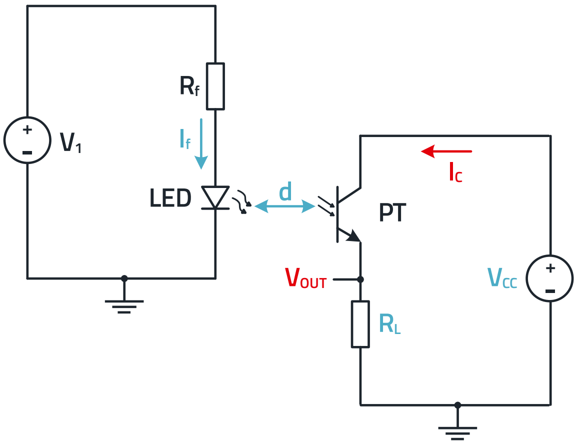

Figure 9: Circuit of the measurement setup with analyzed parameters marked.

3. COLLECTOR CURRENT AND OUTPUT VOLTAGE AS A FUNCTION OF VARIOUS PARAMETERS

The circuit shown in Figure 9 is used to analyze the collector current and output voltage with various circuit parameters. The most important parameters for understanding are listed below:

- IR-LED current, I_f
- Distance between IR-LED and PT/PD, d
- Supply voltage, V_{CC}
- Load resistance, R_L

3.1 LED current

The relationship between illuminance and collector current was shown in Figure 2. In addition, the ratio between LED current I_F and radiant intensity is shown in Figure 4. By combining this information, it can be concluded that the higher irradiance resulting from increased LED current leads to a rise in collector current on the detector side. As both relationships are linear, their combination is linear. This applies to both the phototransistor (Figure 10) and the photodiode (Figure 11).

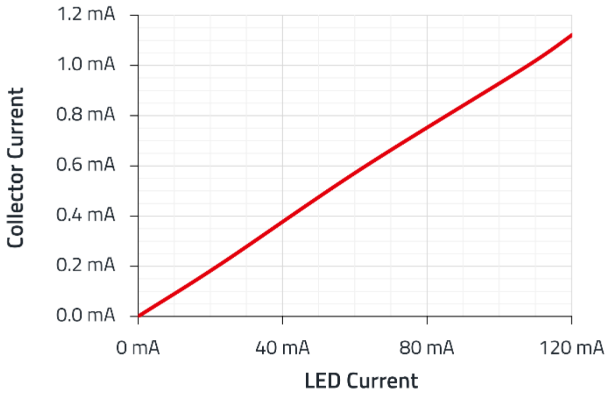

Figure 10: Collector current I_{CE} against LED current I_f at a constant distance (154141185A3011 to 1541411NEA210 at R_L = 50 Ω and V_{CC} = 10 V).

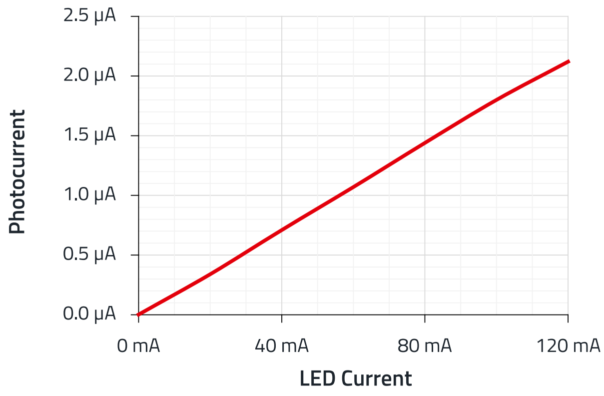

Figure 11: Photocurrent I_P against LED current I_f at a constant distance (154141194A3011 to 1541141ECA570 at R_L = 50 Ω and V_{CC} = 5 V).

The output voltage follows a linear relationship, as Ohm's law applies according to equation (2).

3.2 Distance

When designing emitter-detector circuits, the distance d between the two components, “emitter” and “detector”, is one of the most important parameters. It can be seen in Figure 12 (for phototransistors) and in Figure 13 (for photodiodes) that the collector current I_C decreases quadratically with increasing distance.

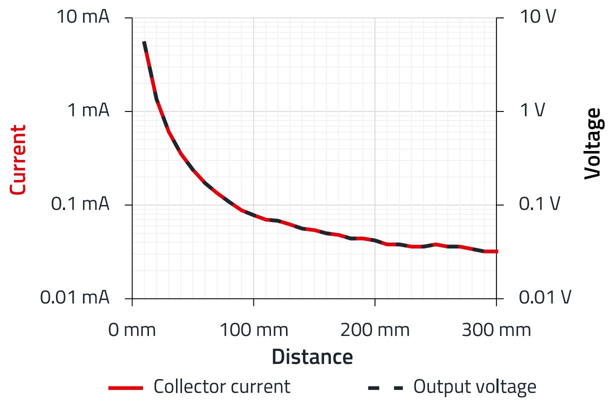

Figure 12: Collector current I_{CE} and output voltage V_{OUT} against distance d (15412094A3060 to 1541201NBA300 at I_F = 20 mA, V_{CC} = 10 V and R_L = 1 kΩ).

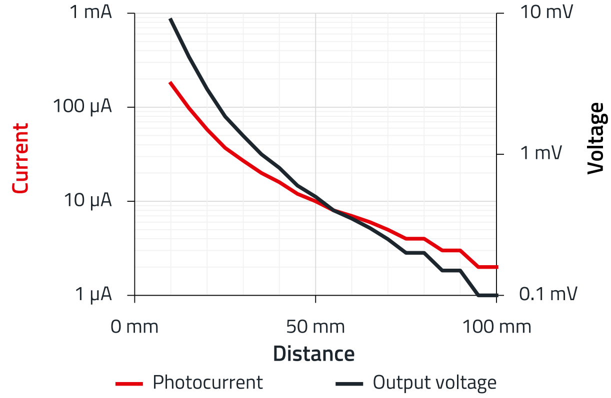

Figure 13: Photocurrent I_P and output voltage V_{OUT} against distance d (15414194A3011 to 1541141ECA570 at I_F = 100 mA, V_{CC} = 5 V and R_L = 50 Ω).

This can be explained by the distance law, which defines the following proportionality between irradiance E_e and distance d[2]:

$$E_e \sim \frac{1}{d^2} \qquad (4)$$

Additionally, if we refer to the, linear relationship between irradiance and collector current or photocurrent, as shown in Figure 4, the relation from (4) can be additionally modified. Taken into account the linearity of Ohm’s law and the Output voltage from eq. (1), (2) we can define the relation of the output signal to distance as follow (5):

$$V_{out} \sim \frac{1}{d^2} \qquad (5)$$

3.3 Supply voltage

For phototransistors, the relationship between collector current and supply voltage in Figure 14 applies.

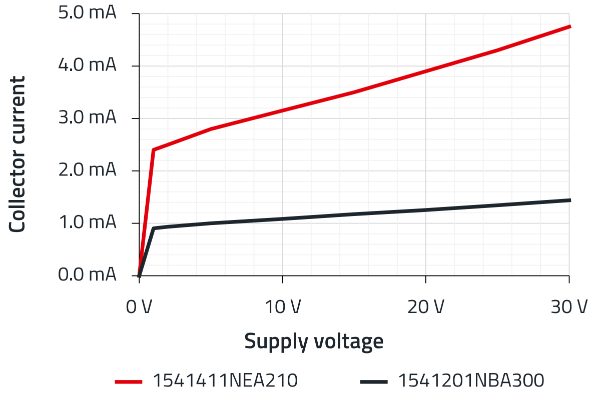

Figure 14: Collector current I_{CE} against supply voltage V_{CC} for various phototransistors (15414185A3011 at I_F = 100 mA and R_L = 50 Ω).

Here it is shown that different phototransistors exhibit varying degrees of dependence on the supply voltage.

This profile corresponds to the relationship between collector current and collector-emitter voltage described in the datasheet. The following applies to the relationship between supply voltage, collector-emitter voltage, and output voltage (6):

$$V_{CC} = V_{CE} + V_{OUT} \qquad (6)$$

The curves shown have strong similarities with the characteristic curve of a bipolar transistor, with irradiance replacing the base current. In this relationship, a set of characteristic curves can be defined with the following ranges:

- Saturation range: $V_{CE} \leq V_{CE,SAT}$
- Cutoff range (separation range): $V_{CE} > 0$ & $E_e = 0$, $I_{CE} \approx 0$
- Active region (forward-active region): $V_{CE} > V_{CE,SAT}$

Typical set of characteristic curves of a phototransistor is shown in Figure 15.

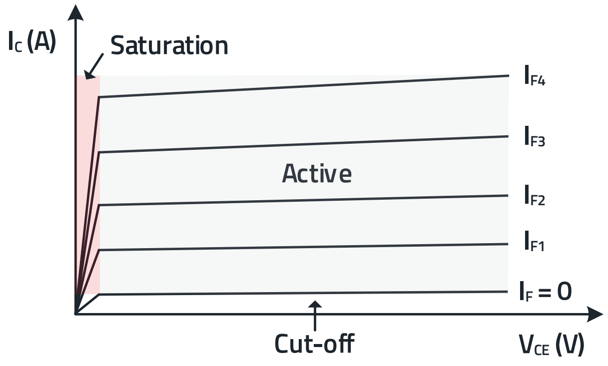

Figure 15: Typical set of characteristic curves of a phototransistor.

When selecting the supply voltage V_{CC} it is important to note that both the collector current I_C and the output voltage V_{OUT} have a maximum value. These maximum values are defined by Ohm's law: $I_C < V_{CC} / R_L$. For the output voltage, $V_{OUT} < V_{CC}$ applies, as equation (2) applies here.

This relationship can be seen in Figure 16.

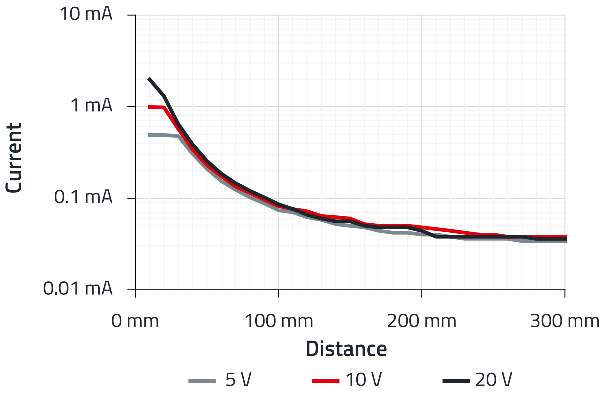

Figure 16: Collector current I_{CE} against distance d at different supply voltages V_{CC} and with limitations (15412094A3060 to 1541201NBA300 at I_F = 20 mA and R_L = 10 kΩ).

For photodiodes, a similar relationship applies between photocurrent and supply voltage as for the phototransistor (see Figure 17).

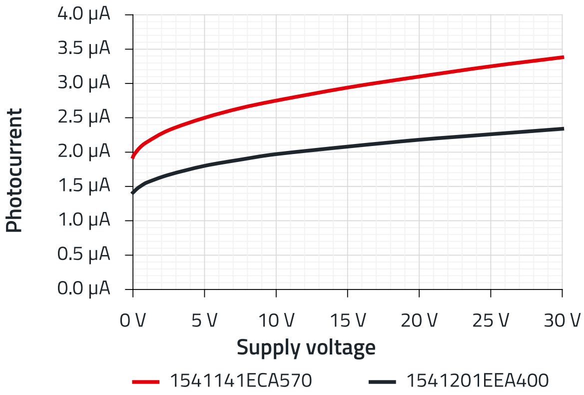

Figure 17: Photocurrent I_P against supply voltage V_{CC} for different photodiodes (15414194A3011 at I_F = 100 mA, R_L = 50 Ω and E_e = 1 mW/cm^2).

However, the same clearly defined ranges, as in the case of the phototransistor, are not identifiable. Nevertheless, different photodiodes exhibit varying degrees of dependence on the supply voltage.

The profile shown in Figure 17 corresponds to the expected behavior based on the (photo) diode characteristic curve. According to theory, the reverse current rises with increasing voltage. Like the phototransistor, the voltage across the photodiode is directly linked to the supply voltage (7).

$$V_{CC} = V_{DIODE} + V_{OUT} \qquad (7)$$

3.4 Load resistance

The appropriate load resistance for a specific application depends on the parameters discussed earlier.

Figure 18 shows that the output voltage rises almost linearly with increasing load resistance.

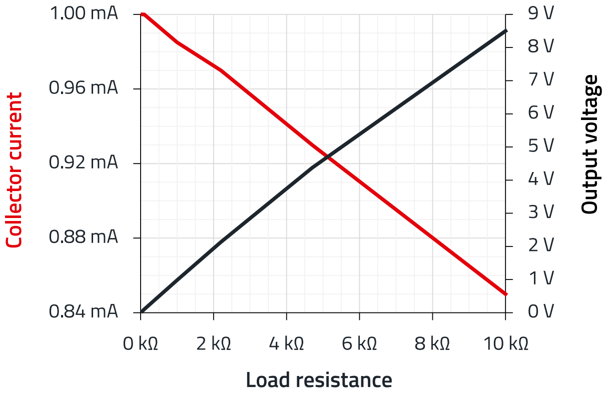

Figure 18: Collector current I_{CE} and output voltage V_{OUT} against load resistance R_L at constant illuminance (15414185A3011 to 1541411NEA210 at I_F = 120 mA, V_{CC} = 20 V and d = 60.5 mm).

The fact that this is the case follows from equation (2). However, the profile is not perfectly linear, as the collector-emitter voltage decreases with increasing output voltage ($V_{CE} = V_{CC} - V_{OUT}$). This leads to a drop in collector current, as shown in Figure 6. In combination with equation (2), this results in the output voltage profile shown in Figure 18.

While the collector current shows only minor changes with variations in load resistance (~µA/kΩ), the change in output voltage is significantly greater. In applications, this means that a larger load resistance results in a higher output voltage. In most cases, the influence of the collector current is negligible, and the relationship between load resistance and output voltage can be assumed to be linear.

For the photodiode, there is a similar dependence on the load resistance as with the phototransistor. The cause is the same and is related to the supply voltage curve shown in Figure 17. As the profile is exponential, the behavior of the photodiode has an exponential characteristic.

The collector current decreases, and the output voltage does not increase linearly. In this case, since the photocurrent and output voltage are low, these changes are not negligible and need to be considered (Figure 19).

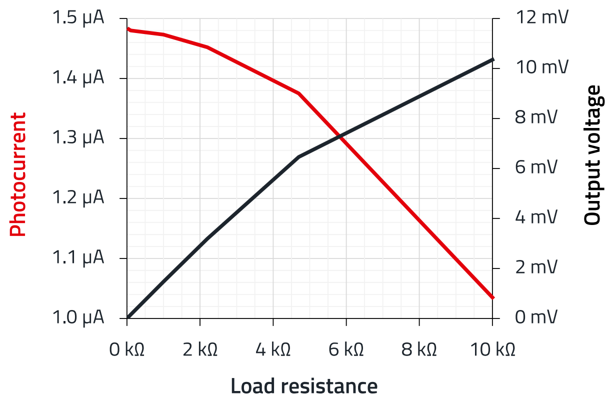

Figure 19: Photocurrent I_P and output voltage V_{OUT} against load resistance R_L at constant illuminance (15414194A3011 to 1540051EC3590 at I_f = 100 mA, V_{CC} = 10 V and d = 20 mm).

3.5 Summary

The graphs shown clearly indicate that various parameters influence the collector/photocurrent and the output voltage. Table 1 summarizes the effects of the individual parameters.

Parameter	Collector current I_{CE}	Photocurrent I_P	Output voltage V_{OUT}
LED current I_f	Increases linearly	Increases linearly	Increases linearly
Distance d	Decreases with $^1/_{d^2}$	Decreases with $^1/_{d^2}$	Decreases with $^1/_{d^2}$
Supply voltage V_{CC}	Increases linearly	Approaches a value exponentially	Increases linearly
Load resistance R_L	Decreases approximately linearly	Decreases exponentially	Increases approximately linearly

Table 1: Effects of the parameters on the collector current I_{CE} and output voltage V_{OUT}.

This information serves as a basis for designing applications that include the IR LED and photodetector.

However, as shown in 3.3, the collector current and the output voltage are limited by the supply voltage.

In applications, there are several approaches to counteract a low output signal:

- Increasing the LED current, I_f
- Reducing the distance, d
- Increasing the supply voltage, V_{CC}

In addition, increasing the load resistance R_L can achieve a higher output voltage V_{OUT}.

If the listed options are not sufficient, it is possible to use amplifier circuits with OP amps or transistors to amplify the signal.

4. SWITCHING TIME

As mentioned earlier, an IR LED is used to analyze the switching times, as it has significantly shorter rise and fall times ($t_{r/f}$ < 100 ns) than the phototransistor.

The rise and fall times are typically measured across the load resistor R_L. The circuit with the marked parameters is shown in Figure 20, which are:

- collector current, I_{CE}
- distance between IR-LED and photodiode, d
- supply voltage, V_{CC}
- load resistance, R_L

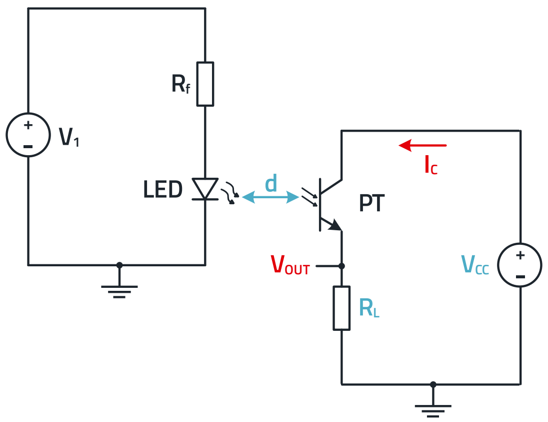

Figure 20: Circuit parameters for measuring the switching time.

4.1 Collector current

Now that the behavior of the collector current under various parameters has been explained, Figure 21 shows how the switching time varies with the collector current.

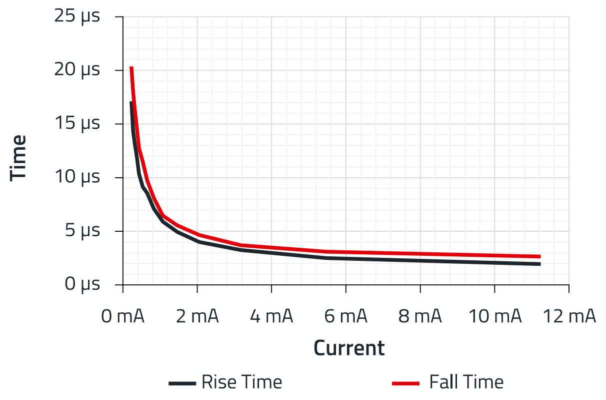

Figure 21: Rise time and fall time against collector current I_{CE} (15414185A3011 to 1541411NEA210 at I_F = 100 mA, V_{CC} = 10 V and R_L = 50 Ω).

The rise and fall times are inversely proportional to the collector current and are significantly shorter at higher collector currents. In general, the fall time is usually longer than the rise time.

4.2 Distance

It has been shown that the collector current decreases sharply as the distance increases. For the switching times, this means that at greater distances, the rise and fall times increase, see Figure 22.

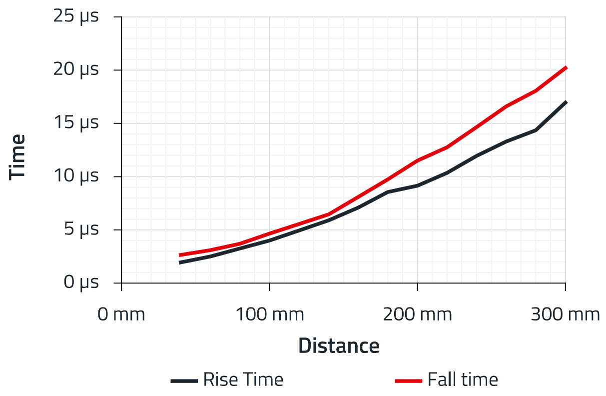

Figure 22: Rise time and fall time against distance d (15414185A3011 to 1541411NEA210 at I_F = 100 mA, V_{CC} = 10 V and R_L = 50 Ω).

Combining equation (3) and equation (4) shows that the relationship is quadratic. This means that the collector current decreases with $1/d^2$ and the switching times increase with $1/I_{CE}$.

4.3 Load resistance

In Figure 23, the profile of the switching times against load resistance is shown.

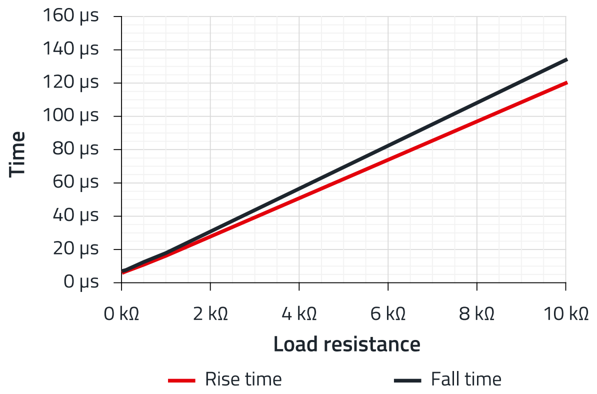

Figure 23: Rise time and fall time against load resistance R_L (15414185A3011 to 1541411NEA210 at I_F = 100 mA, V_{CC} = 10 V and E_e = 1 mW/cm^2).

The relationship shown is linear.

As previously explained, these delays are caused by parasitic capacitances, among other factors. The exact theoretical relationship is shown in equation (3). A simplified approach is to compare this to the charging and discharging process of a capacitor. The time constant is given by: $\tau = R \cdot C$. To illustrate the process, this relationship can be applied to the parasitic capacitances of the phototransistor. This clearly explains the linear profile of the switching times against resistance.

4.4 Supply voltage

The relationship between the rise and fall times and the supply voltage is shown in Figure 24.

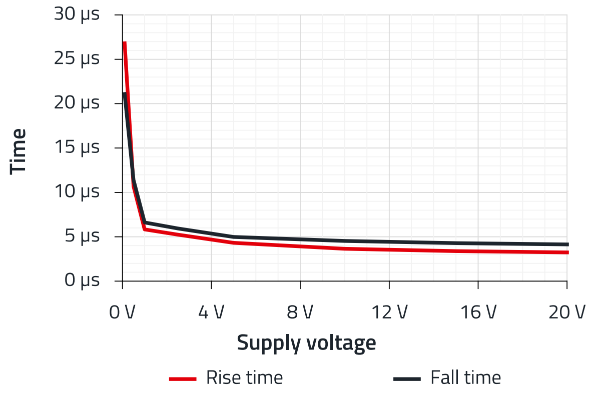

Figure 24: Rise time and fall time against supply voltage V_{CC} *at constant load (154141185A3011 to 1541411NEA210 at* I_F *= 100 mA,* R_L *= 100 Ω and* E_e *= 1 mW/cm²).*

It resembles an inverted phototransistor characteristic curve, indicating that – with a lower collector current in the saturation range – the switching time is significantly longer than in the active region. This relationship arises from the fact that the connection between switching time and collector current is inversely proportional. Here too, the dependence of rise and fall times on the supply voltage varies between phototransistors. It becomes clear that, like a bipolar transistor, it is important to operate the phototransistor in its active range.

4.5 Results

For an overview, the key findings are summarized in Table 2, which can be seen as a basis for circuit design with phototransistors.

Parameter	Impact on switching time
Collector current	Decreases with $\frac{1}{I_{CE}^2}$
Distance	Increases with d^2
Supply voltage	Decreases linearly
Load resistance	Increases linearly

Table 2: Impacts of the parameters on the switching times.

The switching times depend strongly on the collector current, which means that the distance between emitter and detector can significantly influence the switching time. In addition, a suitable supply voltage must be selected to operate the phototransistor in the active range. However, it is especially important to note that improper load resistance can lead to a significant increase in switching time.

5. SUMMARY

The general relationships should now be clear for practical application. The next step is to effectively link these relationships and select the appropriate components and settings. This will depend on the applications at hand – and the geometric description. What is the detection length? Do we have background noise? Etc..

In summary, it can be said:

- LED current: A higher LED current leads to a higher irradiance and therefore to a larger output signal and shorter switching times (until the system is saturated).
- Distance: A greater distance between the LED and receiver reduces the irradiance (≈ $1/r^2$), resulting in smaller output signals and longer switching times.
- Supply voltage: A higher supply voltage increases the available output voltage swing and can improve the switching speed, especially by avoiding deep saturation.
- Load resistance: A larger load resistance leads to a larger output signal, but at the same time increases the time constant (RC) and therefore the switching times.

With the goal of achieving short switching times and high output signals, almost all parameters influence both output signal and switching time, either positively or negatively.

This means that a higher LED current, a shorter distance, and a high supply voltage, can generally be optimized to achieve a higher and faster output signal. The exception here is the load resistance, as it increase results in a higher output signal and in longer switching times. A compromise between signal amplitude and speed must be found for the application.

This information can now be used to design simple circuits, and it helps to understand behavior in more complex applications.

A APPENDIX

A.1 Literature

[1] S.M. Sze, Kwok K. Ng, "Physics of Semiconductors", April 2006

[2] Francisco Vera et al 2014 Eur. J. Phys. 35 01501

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REVISION HISTORY

Document Version	Release Date	Changes
ANO014a	2026/05/04	Initial release of the application note

Note: *The current version of the document and the release date are indicated in the footer of each page of this document.*