"Faster Switching" from "Standard Couplers"

Optocouplers offer tremendous advantages in minimizing EMI and noise susceptibility. It is not an exaggeration to say that a healthy sprinkling of opto-isolation has often meant the difference between a "good idea" and working product. Yet, these very useful devices are often overlooked as possible solutions in designs because they are perceived to be "slow". It is true that there are some limitations due to the inherent underlying technology involved in optocoupler manufacture. In spite of these limitations, with enlightened design principles, "standard" couplers can be used well into the msecond range, or in the case of high-performance couplers, well into the realm of nanosecond switching times.

Some of the higher-speed applications require specialized but widely available "high-speed" couplers. Vishay manufactures and sells high-speed couplers ranging from the 1 Mbd range up to the 10 Mbd range. These couplers can be used in applications were safety and/or noise isolation is required without sacrificing switching performance.

Applications employing lower-performance "standard couplers" can still be optimized for switching speed. Though it can not be expected that these devices perform to the level of specialized "high-speed" devices, they can be more than adequate for many switching applications, up to the 1 µs range. These standard couplers are the subject of discussion in this document. They fall into two general categories, 4 pin couplers, 6 pin couplers, as well as a special configuration of the single transistor coupler. This "photo diode" configuration can be schematically considered as the diode detector version seen in figure1.

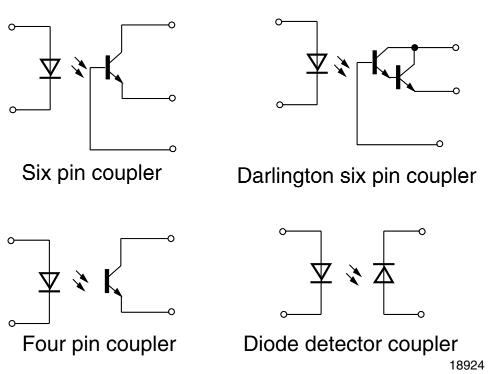


Fig. 1

In this discussion, we concentrate on the common emitter and common collector switching circuits illustrated on figure 2. Which of these is most appropriate will be discussed later on.

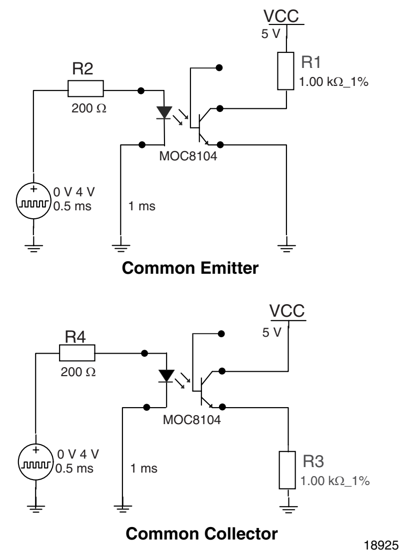


Fig. 2

The definition for t_{off} and t_{on} used in this document will be as per the drawing on figure 3.

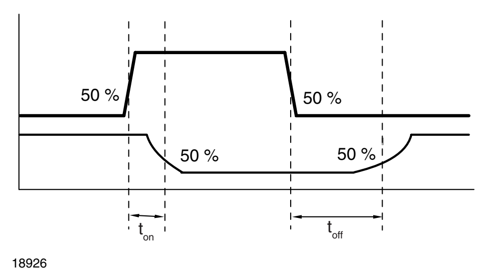


Fig. 3

In general, the factors that affect the transient response of optocouplers are, in order of importance, as follows:

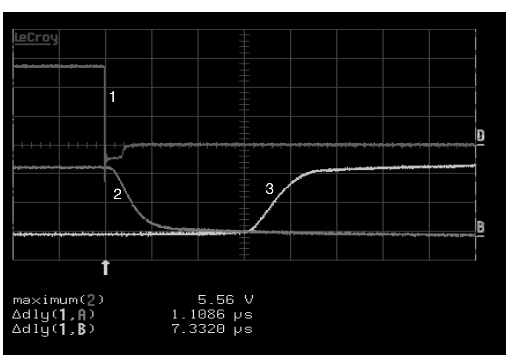
1. I_C or collector or emitter load resistor
2. R_{BE} resistor value
3. Phototransistor current gain (h_{FE})
4. Transistor junction capacitance
5. C_C vs. C_E configuration - Miller effect
6. Speed of the LED

LED VS. PHOTOTRANSISTOR DELAYS

Sub 10 µs performance can be easily achieved with inexpensive transistor output couplers. Of these two types of standard couplers, the 4 pin variety is probably the most ubiquitous and inexpensive available. It is also the coupler that has the least number of options, in terms of switching speed performance optimization. About the only thing that can be done to optimize the switching speed of these parts is to adjust the load and LED drive currents.

Although there are switching limitations on the part of the emitter LEDs, in most cases these are insignificant in comparison to the switching limitations of the phototransistor portion of couplers. Typical LEDs used in optocouplers have switching times that are well below 100 ns. Consequently, the dominant concern when dealing with standard optocoupler switching time response is the phototransistor. Even if extreme measures are taken to reduce the switching delay of standard optocouplers, the LED delay only comes into play when overall speeds are reduced to the hundreds of nanoseconds. Consequently, for the purpose of this document, LED switching is assumed to be instantaneous.

The overwhelming dependence on the phototransistor of the overall transient response of an optocoupler is illustrated in the oscilloscope waveforms shown in figures 4 and 5. The first figure shows the input and output waveforms of common emitter and common collector configured outputs with a 1 k load resistor and a 100 k resistor connected from the base to ground, with the phototransistor being driven by the photo current of the LED. The second scope plot differs from the first in that it does not rely on photo current to drive the base of the phototransistor, but drives it directly using a 100 k base resistor. From the stricking similarity between the two plots, one can conclude that the LED contribution to total switch delay is negligible.



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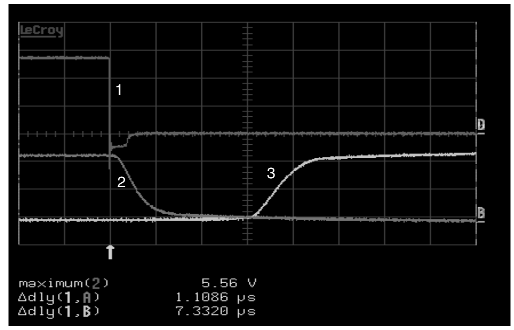
1 trace = input current
2 trace = C_C configuration
3 trace = C_E configuration

Fig. 4 - LED-Driven Optocoupler



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1 trace = input current
2 trace = C_C configuration
3 trace = C_E configuration

Fig. 5 - Direct Base-Driven Optocoupler (no LED Delay)

PHOTOTRANSISTOR BASICS

To make couplers more optically sensitive and thereby necessitate lower LED drive currents, it is desirable to employ sensitive phototransistors with high current gain. A more sensitive phototransistor translates into a larger base area, which allows for the collection of more photons and thereby greater photo current. Unfortunately, with larger base collector junction area comes greater C_{BC} (base collector capacitance). But C_{BC} will decrease with increasing V_{CB}, as illustrated in figure 6. Thus, as we decrease the collector voltage, the base region capacitance is increased. This, in turn, increases the amount of time required to bring the base region to a neutral charge equilibrium.

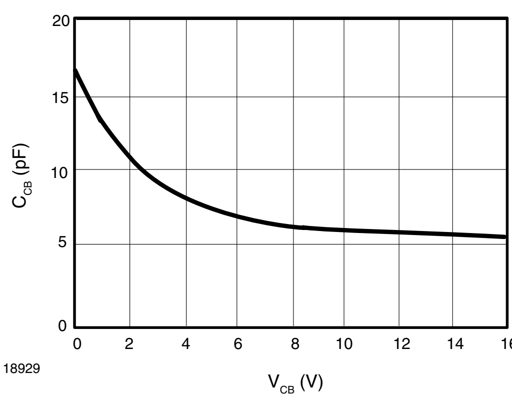
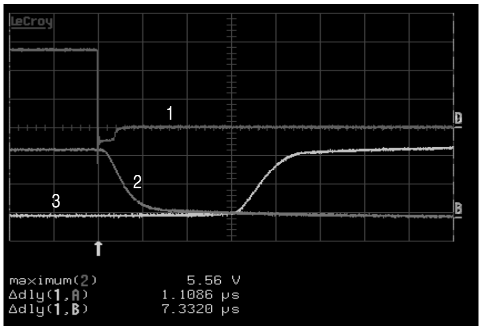


Fig. 6 - C_{CB} vs. V_{CB}

Note that the capacitance being discharged is not simply C_{BC} but C Miller, and in certain circuit configurations this can have a tremendous effect on transient response. More about C Miller will be said in the Miller capacitance section of this document. The inherent difference between the transient response of a standard transistor and a phototransistor can be clearly seen in the oscilloscope plots in figures 7 and 8. Figure 7 is a transient response of a photo transistor, while figure 8 is a typical response of the venerable 2N3904 NPN transistor. The inherently slower speed of the phototransistor is clearly demonstrated. The top trace is the input current while the two bottom traces depict the C_E and C_C output waveforms respectively.



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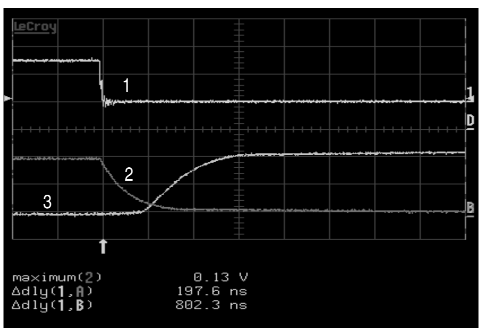
1 trace = input current
2 trace = C_C output
3 trace = C_E output

Fig. 7 - Photo-Transistor Response



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1 trace = input current
2 trace = C_C output
3 trace = C_E output

Fig. 8 - 2N3904 Discrete BJT Response

In the case of a 4 pin transistor output coupler, there is no effective mechanism for charge bleeding from the base region other than natural charge recombination and the slow process of discharge through the large equivalent base resistance. Consequently, all that can be done to optimize the switching time of a 4 pin standard coupler is to refrain from driving the base junction region of the transistor "deep" into saturation, as much as possible. This translates into working with lower gains and higher drive currents (I_F). In other words, one is forced to trade power consumption for speed. For those old enough to remember the days of ECL logic, this should be a familiar trade-off. Fortunately, the 6 pin version of the standard BJT output coupler, with a base pin, offers more options for transient speed optimization than the standard 4 pin variety.

PHOTOTRANSISTOR CHARGE-BASED ANALYSIS THEORY

This portion will try to give a qualitative understanding of the mechanisms involved in the cutoff to saturation switching of BJTs. If the reader has not any interest in this subject and just wishes to get the practical load and drive current (I_F) values, it is advised that this section be skipped and go directly to the load curves starting, at page 6 of this document.

Probably the best way to approach the question of switching speed in saturation conditions is from the point of view of charge storage in the base region. The equations that govern the behavior of charge transport are quite simple to understand, and shed some light into understanding the physical mechanisms involved.

The charge approach is "water-tight" from a conceptual point of view, and for practical analysis one most often has to rely on empirical data, regardless of the theoretical approach taken. The first concept to consider is the simple one of charge balance, and it is stated below as:

$$i_B(t) = \frac{Q_b(t)}{\tau_p} + \frac{Q_b(t)}{dt}$$

In plain English the above equation states that the current flowing into the base must equal the forcing current into the base minus the rate of charge lost to recombination in the base region and the carriers that are injected across to the emitter from the base region. The recombination loss is quantified by the average minority carrier recombination lifetime time constant τ_p (in the case of an PNP and τ_e in the case of an NPN), or in other words the average time it takes for a carrier to recombine in the base region. Another constant to keep in mind is the average time a charge carrier spends in transit across the base region, τ_t. In a BJT, τ_p is much larger than τ_t. This is the key to the current amplification characteristic of the BJT transistor, and is illustrated by the charge current relationship outlined below.

For a turn-on transient:

$$\frac{i_c}{i_t} = \beta = \frac{\tau_p}{\tau_t} \tag{1}$$

From these parameters a relationship can be derived that will allow one to obtain the turn-on transient time, given these time constants. In reality this is of limited practical value because the key parameters are not available to the designer; however, it is a very important set of tools for conceptual understanding.

For a turn-on transient:

$$Q_b(t) = I_B\tau_p\left(1 - e^{\frac{-t}{\tau_p}}\right) \tag{2}$$

$$I_C = \frac{I_B\tau_p}{\tau_t}\left(1 - e^{\frac{-t_s}{\tau_p}}\right) \tag{3}$$

Where

$$t_s = \tau_p \ln \frac{1}{1 - \frac{I_C}{\beta I_B}} \quad (4)$$

For a turn-on transient:

$$Q_b(t) = I_b \tau_p \left(2e^{\frac{-t}{\tau_p}} - 1 \right) \quad (5)$$

$$i_C = I_C e^{\frac{-(t - t_{sd})}{\tau_p}} \quad (6)$$

$$t_{sd} = \tau_p \ln \frac{I_B \tau_p}{I_C \tau_t} = \tau_p \ln \frac{\beta I_B}{I_C} \quad (7)$$

The turn-on transient case is included for the sake of completeness; however, the dominant factor in overall switching speed is toff, and this needs to be explored thoroughly.
In actual switching applications, the transistor is more than just saturated, it is in the “super-saturated” state. Consequently, the transistor charge must be dropped form its initial “super-saturated” level of

$$Q_b = I_B \tau_p \quad (8)$$

to the minimum base charge level required for saturation.

$$Q_s = I_c \tau_t \quad (9)$$

This is important to realize because it is not sufficient to concentrate merelyon the exponential discharge portion of t_{off}. Thus, we end up with two equations equation (7), which quantifies the time required to discharge to the minimum be charge level required for saturation, and equations (5) and (6), which govern the charge and current behavior beyond the minimum saturation point.
Again, it is important to reiterate that the BJTs being discussed are not standard transistors but rather phototransistors, which have much larger base regions than would be the case for a standard BJT. Consequently, instead of τ_{ps} in the tens of microseconds and τ_{ts} in the hundredths of microseconds, the time constants encountered with phototransistors are far higher.

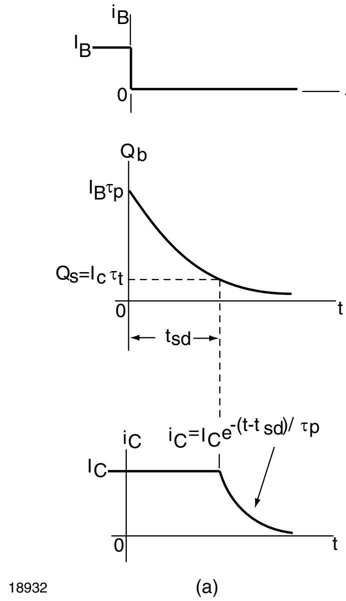


Fig. 9

The curves illustrated in figure 9 graphically represent the relationships involved in the transient discharge cycle of a BJT. A large relatively long t_{sd} is required to get out of the supersaturated mode and start to notice a drop in collector current. The non-symmetry between t_{on} and t_{off} can be seen in figure 10. The charge is the area on the curve of the current waveform and it is equal for the t_{on} and t_{off} cycle; however, as figure 10 illustrates, the far smaller discharge current greatly expands the time involved in the discharge cycle.

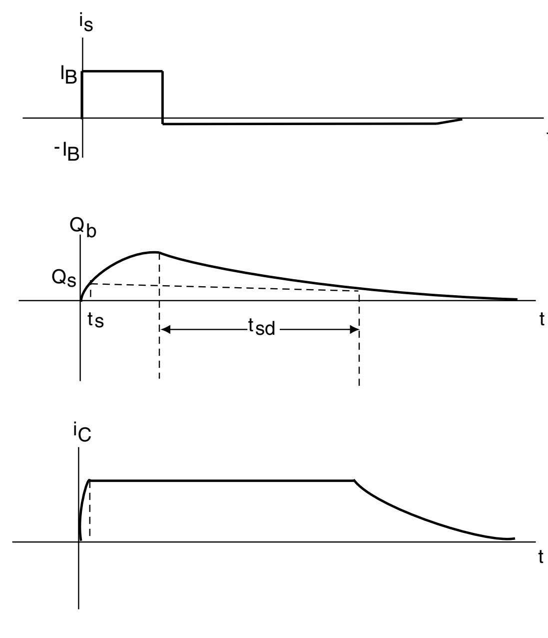


Fig. 10

The previous discussion was included in an attempt to give the reader an appreciation for the mechanisms involved in the transient switching cycles of a BJT. In practice, an analytical approach is often impossible because the parameters required for such analysis are not available. Instead, manufacturers often give curves of R_L vs. t_{on} and t_{off} for various I_F conditions. This is a faster and much more practical approach to an engineering solution than a rigorous analysis. Typical curves for standard BJT phototransistor 4 pin and 6 pin devices are given in the following page. When working with these tables, it is always important to take into account worst-case temperature and CTR conditions.

The data shown in figure 11 demonstrate the effects of increasing CTR on the turn-off transient behavior of optocouplers. The dependence of CTR on t_{off} is actually an indirect measure of its dependence on h_{FE}. However CTR is an approximate but not exact measure of h_{FE}, since CTR is a combination of h_{FE} and LED efficiency.

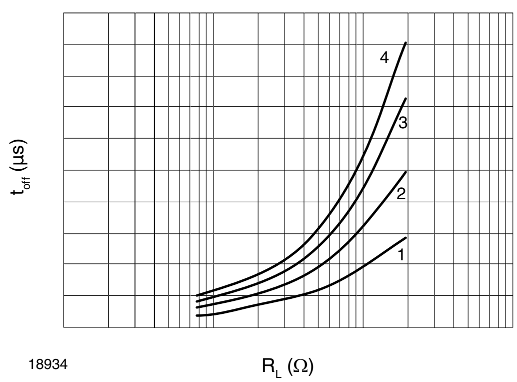
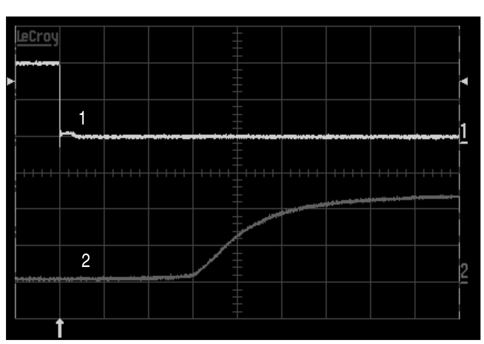


Fig. 11 - t_{off} vs. R_L

Figure 12 includes actual plots of the transient waveforms themselves. Pay attention not only to the quantitative information on these plots but also the shape of the waveforms.



I_F = 20 mA, R_L = 1 kΩ, t_{on}-delay = 1.2285 µs
1 trace = input signal
2 trace = C_E output signal

Fig. 12

Figure 12 illustrates the typical characteristic turn-off behavior of a BJT optocoupler with the output in the common emitter or inverting configuration. There is a small delay between the time the input starts to rise and the time the transistor starts to turn on in an exponential fashion. The straight line portion of the output waveform is accounted for by the time it takes the BJT to get from the super-saturated state to the marginally saturated state.

The curves on page 8 illustrate several important trends that need to be taken into account when attempting to optimize an optocoupler design for minimum switching time:

1. Turn-off time increases with increasing load resistance or decreasing load current. This is easily explained by the fact that the lower the load current the easier it is to drive the opto-BJT into super saturation.
2. Turn-off time increases with increasing CTR. CTR is an indirect measure of h_{FE} (but not an exact measure of this parameter). Thus increasing CTR increases t_{off} for the same reason as explained above.
3. Increasing I_F does have the effect of increasing t_{off} but not by as much as from an increas in R_L and CTR.
4. Increasing R_L, I_F, and CTR slightly increase the turn-on time of the coupler.

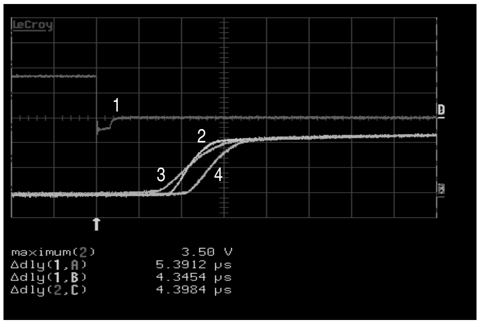
TEMPERATURE EFFECTS ON TRANSIENT RESPONSE

Temperature has a minor effect on transient response, but its effects are somewhat counter-intuitive and in most cases do not play a tremendous role in overall transient response performance.

On the one hand, as junction temperature decreases, the LED becomes more efficient, thereby providing more photo current to drive the phototransistor further into saturation. At the same time that the LED becomes more efficient the h_{FE} of the phototransistor has a positive temperature coefficient and diminishes with decreasing temperature. This h_{FE} diminishing effect more than makes up for the increase in LED efficiency. Thus, as can be seen from the results below, the overall effect of decreasing temperature is to decrease switching time. On the other hand, as the same figure shows, as temperature increases, just the opposite effect takes place, and transient speed decreases with increasing temperature.

As shown in the lab results outlined in figure 13, the effects of increasing temperature above room temperature seem to have a much more significant effect than a reduction in ambient temperature. As a matter of fact, going below room temperature seemed not to have any significant overall effect.

Finally, these results were taken up to 100 °C rather than the maximum ambient operating temperature of 85 °C, for the purpose of being able to obtain more noticeable results.



1 trace = input LED current
2 trace = output at 0 °C
3 trace = output at 25 °C

Fig. 13

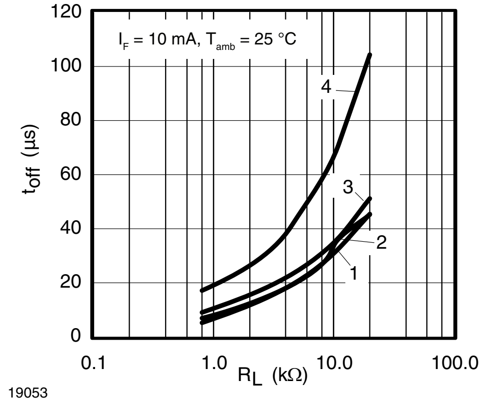


Fig. 16 - t_{off} vs. R_L

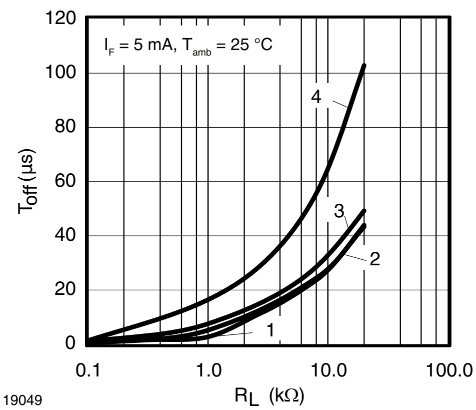


Fig. 14 - t_{off} vs. R_L

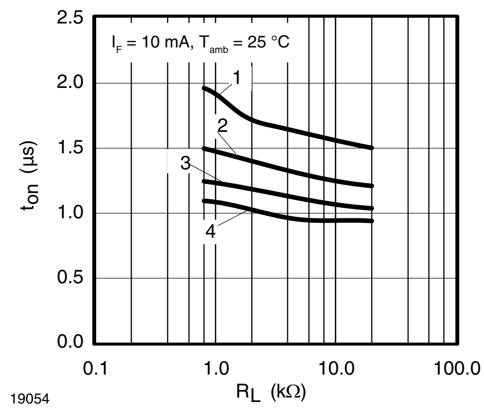


Fig. 17 - t_{on} vs. R_L

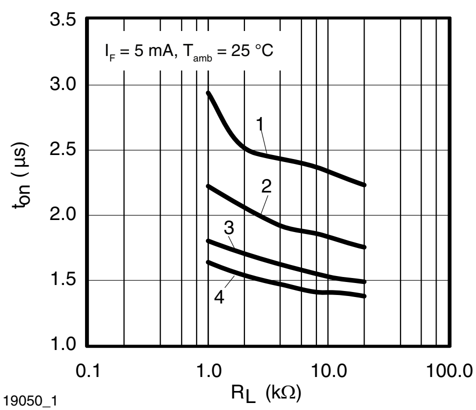


Fig. 15 - t_{on} vs. R_L

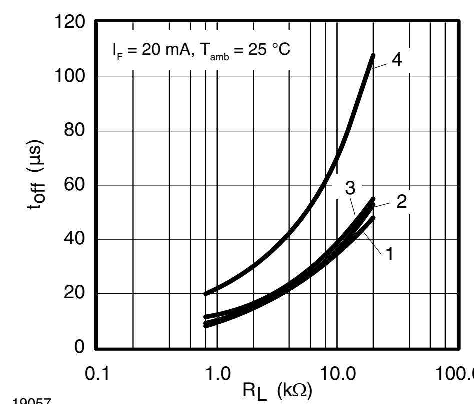


Fig. 18 - t_{off} vs. R_L

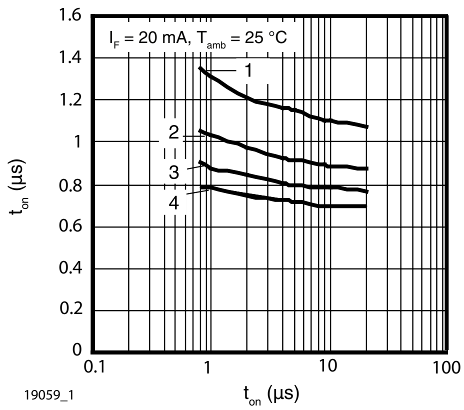


Fig. 19 - t_{on} vs. R_L

BASE EMITTER RESISTOR DISCHARGE

The next step in switching speed improvement is to move from a standard 4 pin part to a standard 6 pin coupler. This type of coupler gives the user access to the base of the phototransistor and allows us to modify the standard common emitter switching circuit discussed above, in the case of the 4 pin coupler, to the one illustrated in figure 20. To determine the R_B required for a specific t_{off}, it is best to be guided by empirically generated tables illustrated on the following page. However, note that the addition of a base-emitter resistor reduces the effective CTR of the coupler in question by draining away a portion of the photo current that would normally go to drive the base of the phototransistor. Consequently, once a value of R_{BE} has been arrived at, it is necessary to get an estimate for the additional I_F required to obtain the same base drive capability. The relationships that govern the calculation of the required I_F for a given R_{BE}, are as follows:

$$CTR = I_C / I_F \qquad (10)$$

$$I_p = I_F \qquad \text{*optical transfer constant} \qquad (11)$$

up to this point nothing changes by adding R_{BE}
without R_{BE}: $I_B = I_p$
If we add R_{BE}

$$I_{b2} = \left(\frac{R_B}{\beta r_e}\right) I_p \qquad (12)$$

where βr_e is the equivalent resistance “looking” into the base of the photo BJT.

Thus

$$CTR_2 = CTR_1\left(\frac{R_B}{\beta r_e}\right)$$

where

$$r_e = \frac{V_{BE}}{I_C}$$

and β or h_{FE} can be measuredusing a curve tracer.
All these results are very β or h_{FE} dependent, of course, and thus constitute a very “slippery” parameter to hang one’s design hat on. Therefore, a very wide margin of engineering tolerance is recommended.

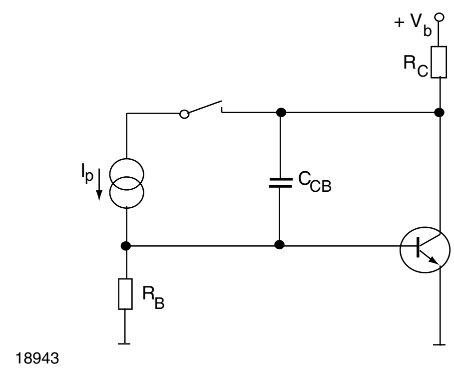


Fig. 20

Practical tip:

When using the curves on the following page, it is important to take into account worst-case temperature and CTR binning conditions. A good practical method for doing this is to take the CTR range of coupler above and below the CTR range that is being considered. If the circuit has operating margin under those conditions, it should have enough margin when using a coupler within the nominal CTR range. This is not an intellectually brilliant approach but it works quite well, and leaves little room for error.

R_{BE} vs. t_{on} and t_{off}

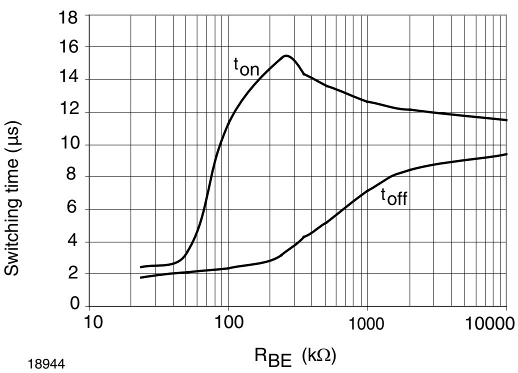


Fig. 21 - Switching Time vs. R_{BE}, I_F = 2 mA

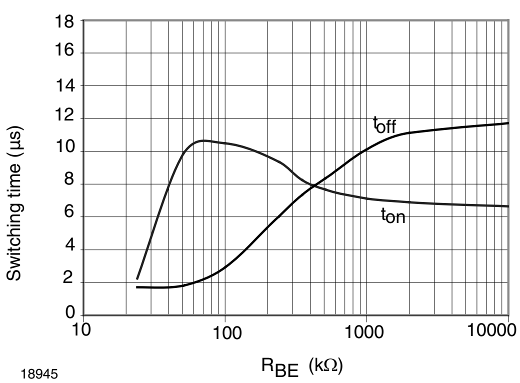


Fig. 22 - Switching Time vs. R_{BE}, I_F = 5 mA

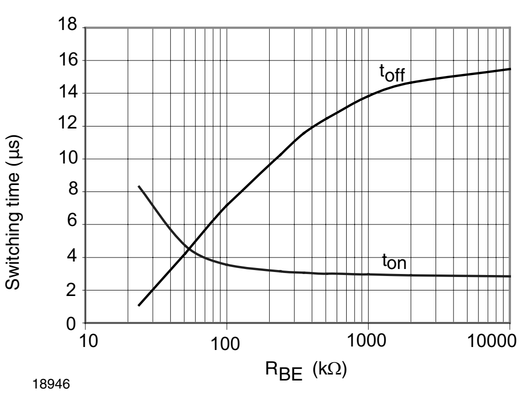


Fig. 23 - Switching Time vs. R_{BE}, I_F = 10 mA

MILLER CAPACITANCE

It is not possible to deal with the issue of transient response without taking into account the Miller effect. In it most general terms, the Miller theorem can be stated as follows:

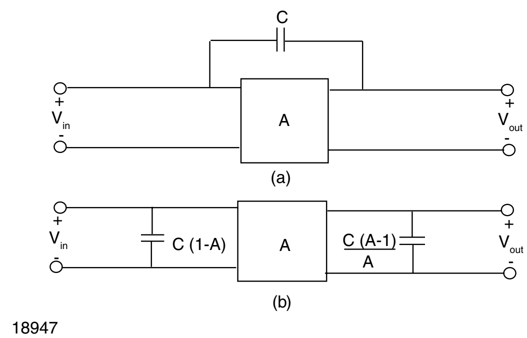
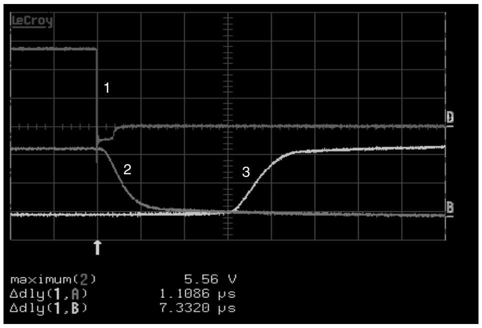


Fig. 24

C in figure 24 is the "feedback" capacitance across a generalized voltage-gain block, where A is the voltage gain. The equivalent Miller capacitance as seen on the output is $C_M = C(1-A_V)$. This is the case that is of interest for the purpose of this document. In the case of the common emitter amplifier configuration, the Miller capacitance formula becomes $C_M = C_{BC}(1+A_V)$, where A_V is the voltage gain of the circuit. The change in sign from the original Miller theorem is due to the inverting nature of the common emitter configuration. While the Miller theorem is very well suited for amplifiers in the case of linear operation where the gain is well behaved and fixed, such is not the case for amplifiers operating from cut-off to saturation. Consequently, getting precise quantitative values using this method of analysis is difficult. The important thing to realize is that the discharge capacitance in question when dealing with a common emitter configuration is not simply the C_{BC} capacitance but rather the much higher Miller capacitance. Also remember that in the case of a "voltage follower" or common collector configuration, with a voltage gain of less than one, the Miller effect results in an equivalent output capacitance that is less than C_{BC}. Thus, in many cases the transient response is much faster with the common collector (voltage follower) configuration than with the common emitter (inverting configuration). The following lab results clearly illustrate the increased turn-off time associated with the Miller effect.

Figure 25 illustrates the difference in Miller effect between the C_C and C_E circuit configurations.



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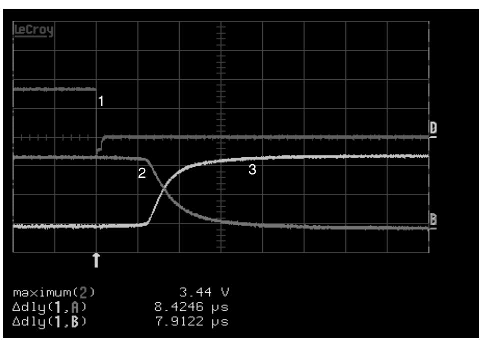
1 trace = input LED current
2 trace = C_C configuration out
3 trace = C_E configuration out
100 kΩ base to ground resistor

Fig. 25

Another limitation of the Miller effect is that it only really becomes apparent when the turn-off mechanism is by means of an active discharge through a base to ground capacitor. In the case where the base is left virtually without any discharge path, the effects of "Miller the killer" are not noticeable, as the results below show. This "Miller indeference" ix illustrated in figure 26.



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1 trace = input LED current
2 trace = C_C configuration out
3 trace = C_E configuration out
base left open without base to ground discharge path

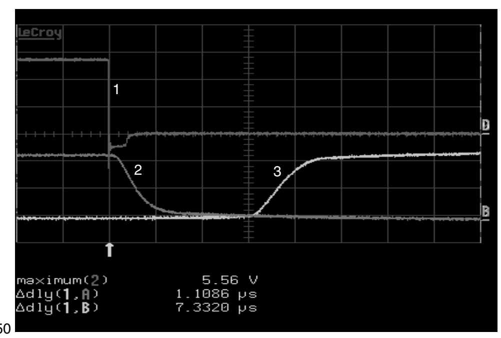
Fig. 26

SPICE SIMULATION ANALYSIS

SPICE is an extremely useful tool in the analysis of optocouplers. As is the case in all simulation techniques, however, the simulation results are only as good as the model. The old maxim of "garbage in garbage out" still holds. Fortunately, in the case of most standard couplers, SPICE models are widely available. Even if a particular part number is not available, it is a fairly straight-forward exercise to take a currently existing model and modify a few parameters to fit the characteristics of the device in question. This document will not go into great detail as to how to develop optocoupler SPICE models. That task is left to another application note on that subject. However, a few key parameters that are needed to investigate transient response performance using standard, widely available SPICE models can be outlined here. The dominant contributor to transient behavior performance in an optocoupler is the detector BJT output stage. Consequently, this discussion will deal with the parameters that can be found in the standard BJT model that most influence switching performance. A standard SPICE BJT model has 21 standard predefined parameters. Of these, the following are pertinent to the problem of switching time:

1. BF = h_{FE} or β
2. CJS = C_{BC}
3. TF = τ_t (transit time)
4. TR = τ_r (recombination time)

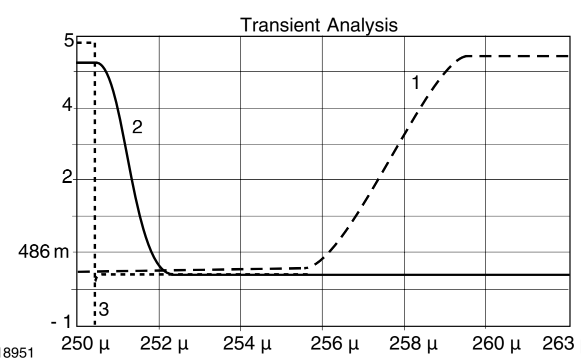
Based on the theory described earlier in this document, these parameters can be manipulated and modified easily to produce simulation results that closely agree with actual experimental results. In the figures below, one can see an example of correlation between SPICE simulation and laboratory results for transient performance in the case of both C_C and C_E circuit configurations.



18950

1 trace = input LED current
2 trace = C_C configuration out
3 trace = C_E configuration out
100 kΩ base to ground resistor

Fig. 27 - Lab Results



18951

1 trace = C_E configuration out
2 trace = C_C configuration out
3 trace = input LED current
100 kΩ base to ground resistor

Fig. 28 - SPICE Simulation

PUSHING THE "SPEED ENVELOPE"

If less than 1 µs t_{off} is required, there are some additional measures that can be taken to further increase the switching time of a standard coupler. At this point, however, economics come into the equation, and a designer needs to consider whether the increased complexity of the design is justified. The other option is to consider one of various parts that are specifically designed for high-speed operation. These devices are discussed in other documents.

PHOTODIODE OPERATION:

One possibility is to give up current gain for the sake of speed in the extreme, and operate a standard transistor coupler in photodiode mode by only using the base collector pins of a 6 pin coupler. This will vastly increase the switching response of the device but will require an output buffering stage to produce a practical signal level. Also, it is possible to further increase the switching speed of this type of coupler by applying an increasingly large reverse bias voltage on the photodiode detector. The effect is to reduce the junction area and capacitance and increase the frequency response. Figures 29 and 30 illustrate two possible approaches to photodiode operation. Figure 29 is the simplest configuration for a photodiode mode of operation. Figure 30 illustrates a photodiode configuration which makes use of a trans-impedance amplifier to provide better gain and noise performance. The key principle of this design is that one can now take advantage of the lower junction capacitance of a simple reverse biased diode rather than the large capacitance of a phototransistor to drastically improve transient performance. This is the basis for the design of most high-speed coupler designs, which will be dealt with in another application-note on high-speed couplers. These couplers usually use high-speed photodiodes to drive more sophisticated amplifier stages and are capable of switching speeds well into the nanosecond range.

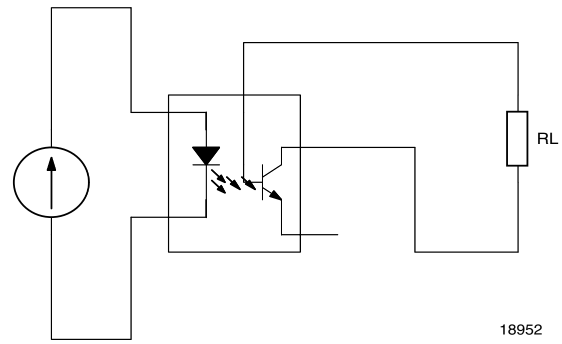


Fig. 29 - Simple Load Resistor Photodiode Circuit

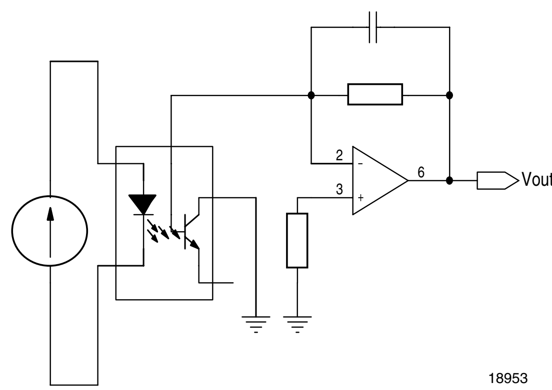


Fig. 30 - Trans-Impedance Amplifier Photodiode Circuit