Speeding Up Optical Isolators

Simple, inexpensive ways to get 3-MHz and greater speed from low-cost optoisolators like the 4N35

By William Melhorn

Electrical isolation between a circuit and the outside world has become a low-cost practical reality with the ready availability of optical isolators like the 4N35 and others. These low-cost optoisolators are excellent devices to use for isolation, as long as the switching rate is limited to a maximum of 22 kHz or so. For faster speeds, in the kilohertz or even low-megahertz range, you have had to resort to high-speed devices that are costly or/and difficult to find from traditional electronic component outlets.

In this article, we will explore simple, low-cost techniques for improving the speed of slow garden-variety optoisolators. Though our discussion will focus specifically on the 4N35 device, most of this discussion applies equally well to other low-speed optical isolators.

Background

An optoisolator can take many physical forms. The low-cost variety commonly available to experimenters and hobbyists, however, usually comes in a six-pin dual in-line package (commonly known as a "DIP") similar to that used for most integrated circuits. Contained within this package are a light-emitting diode, or LED, and a photodetector, the latter usually being a phototransistor. This internal arrangement of a typical optoisolator is shown schematically in Fig. 1(A).

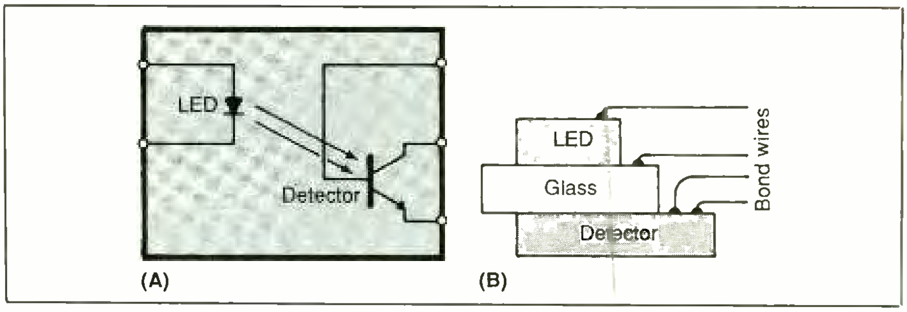

Fig. 1. Schematic (A) and physical construction (B) details of typical optoisolator.

As illustrated in Fig. 1(B), the LED and photodetector are separated inside the package by a thin sheet of optical glass. The glass serves as an efficient medium for coupling the light energy from the LED to the sensitive base of the phototransistor. It also establishes electrical isolation between the two elements. Commonly available low-cost DIP-type optoisolators, such as the 4N35, have an isolation capability that is usually rated at 2,500 volts.

When current flows through the optoisolator's LED diode junction in the forward direction, the LED generates photon energy, or light, as in Fig. 2(A), by a process called "junction luminescence." Excess electrons in the n-type junction material jump the gap of the diode's pn junction and combine with excess holes in the p-type material, as in Fig. 2(B). When these "carriers" re-

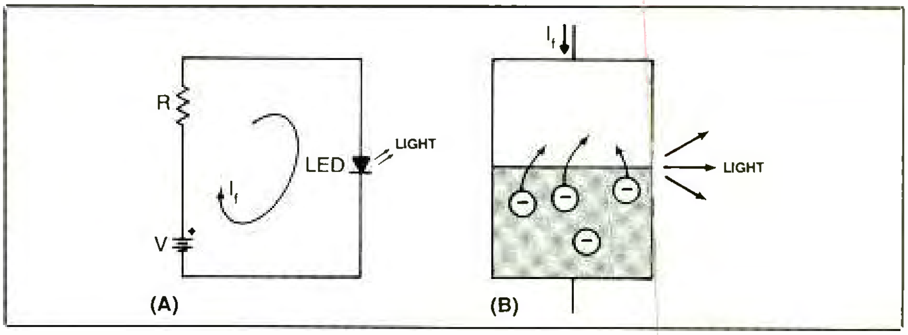

Fig. 2. Forward current flow through a LED results in light-energy output (A). Excess electrons in n-type material jump the gap of a LED's pn junction and combine with excess holes in p-type material to produce light (B).

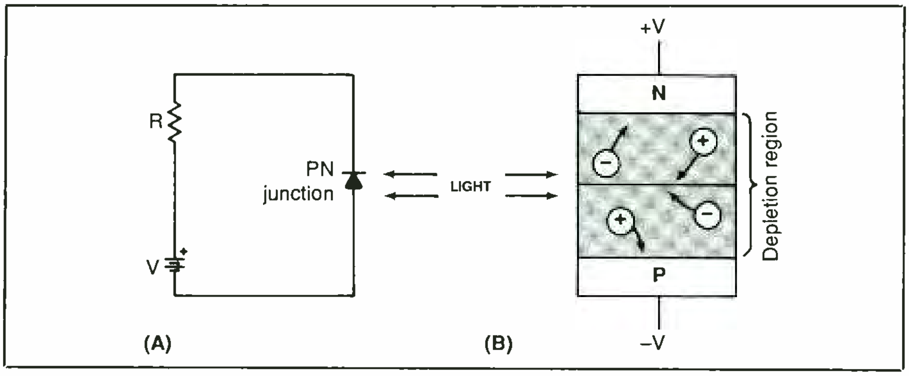

Fig. 3. Reverse-biased phototransistor junction (A) when struck with light from LED generates electron/hole pairs (B) to cause a photocurrent to flow through the phototransistor.

combine, photon energy is released. In the typical optoisolator, this energy is at near-infrared wavelength.

The phototransistor inside the typical optoisolator is sensitive to the infrared energy generated by the on-board LED. When photons strike the reverse-biased collector-to-base junction of the phototransistor, as in Fig. 3(A), electron/hole pairs are generated. As illustrated in Fig. 3(B), these electrons and holes are swept away by the electric field generated by the reverse-bias voltage. The result is a "photocurrent" flow that is proportional to the amount of IR energy striking the junction. The base current in the transistor created by this photocurrent is amplified by the transistor's current gain.

It is at this point in the process that the problem with low-cost general-purpose optoisolators lies. Increasing the phototransistor's junction also increases the sensitivity of the detector simply by making it possible for the detector to collect more photons. However, the larger junction also increases the transistor's inherent capacitance and storage time, which greatly slows switching speed.

A good way to think of this speed-robbing capacitance effect is by reviewing the charging and discharging formulas for the capacitor in a simple RC circuit. The formula for charging a capacitor is:

$$V = V_{max} (1 - e^{-t/RC}),$$

where V is the transistor's collector voltage; V_{max} is supply voltage; R is a resistance whose value is set by the amount of light striking the transistor's collector-base junction; and C is the reverse-biased phototransistor's junction capacitance. According to the data sheet for the 4N35 optoisolator, collector-to-base junction capacitance is about 100 picofarads.

The formula for discharging a capacitor is:

$$V = V_{max} \times e^{-t/RC}$$

In this formula, the terms are determined by the same factors that apply in the charging formula, except that *R* is now set by the phototransistor's base input resistance. Base input resistance for the Fig. 4(B) circuit is the value of the collector resistor multiplied by the transistor's current gain (typically about 100).

For this discussion, the "on" switching time is defined as the difference in time between the point at which the V_{in} input signal switches high and that at which the V_{out} output reaches 90 percent of the supply voltage (see Fig. 5).

The "off" switching time is defined as the time between the points at which the V_{in} input signal goes low and the V_{out} output reaches 10 percent of the supply voltage.

Solving the Problem

To demonstrate how a typical low-cost optoisolator performs, let us conduct an experiment using the commonly available 4N35 device. Assuming the circuit for this experiment is as shown in Fig. 6(A), a 10-kHz signal is applied at V_{in} and

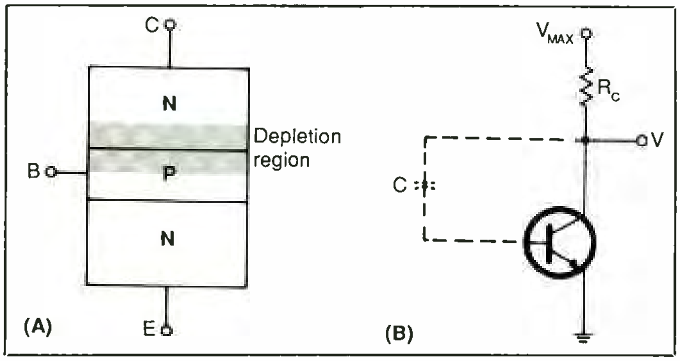

Fig. 4. Physical (A) and schematic (B) capacitance speed-robbing effects of increased junction area.

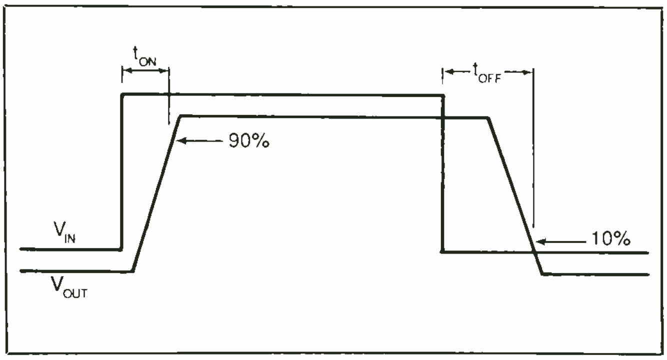

Fig. 5. Graphic illustration of turn-on (t_{on}) and turn-off (t_{off}) times of a typical low-cost optoisolator.

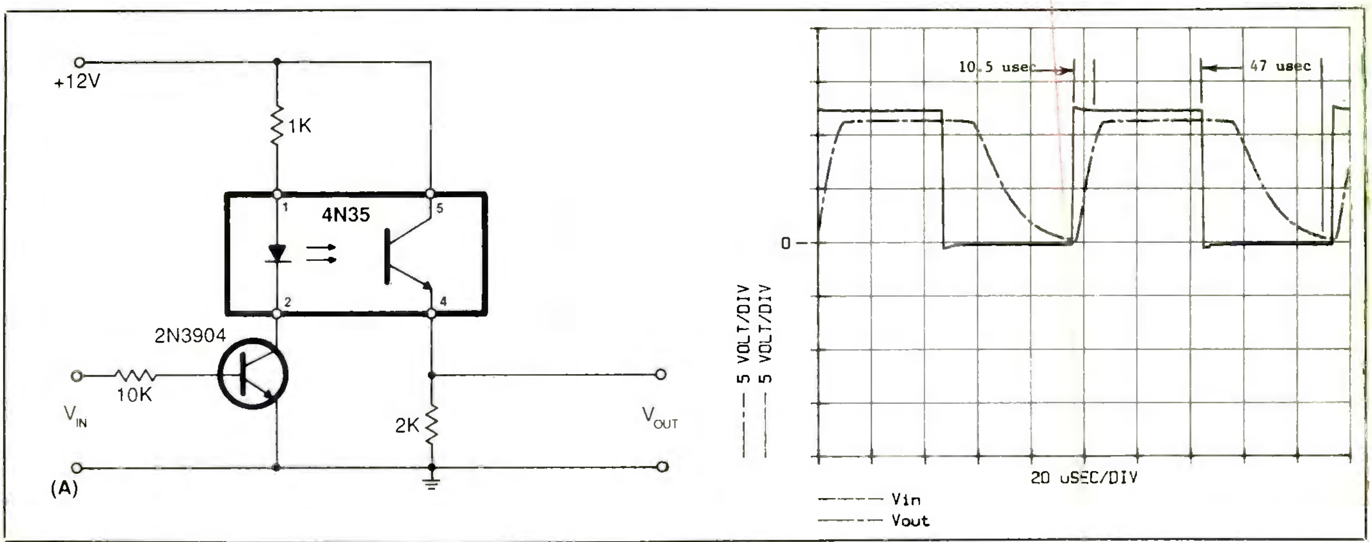

Fig. 6. Schematic of an unassisted 4N35 optoisolator circuit (A) and its switching-speed response (B).

the input signal to and output signal from the optoisolator are monitored on the screen of an oscilloscope.

When V_{in} goes to + 12 volts, the 2N3904 transistor conducts and causes current to flow through the LED inside the 4N35 optoisolator. With current flowing, the internal LED emits IR energy that is, in turn, coupled to and turns on the 4N35's phototransistor. When the phototransistor turns on, its emitter is pulled up to the collector voltage and produces a high output condition at V_{out}.

When V_{in} goes to 0 volt, the 2N3904 transistor turns off and, in turn, shuts off the current through the 4N35's internal LED. With the LED now off, no IR energy is available to keep the internal phototransistor conducting. With this cutoff condition at the output of the optoisolator, a low output condition exists at V_{out}.

For the circuit shown in Fig. 6(A), the length of time needed for turn-on was 10.5 microseconds, and the time for turn-off was 47 microseconds, as illustrated in Fig. 6(B). Notice here how the output waveform has the characteristic shape of a charging and discharging capacitor in an RC circuit.

Trying to improve switching speed, you can add an output transistor to the circuit, as shown in Fig. 7(A). With this stage added, IR energy from the 4N35's internal LED strikes

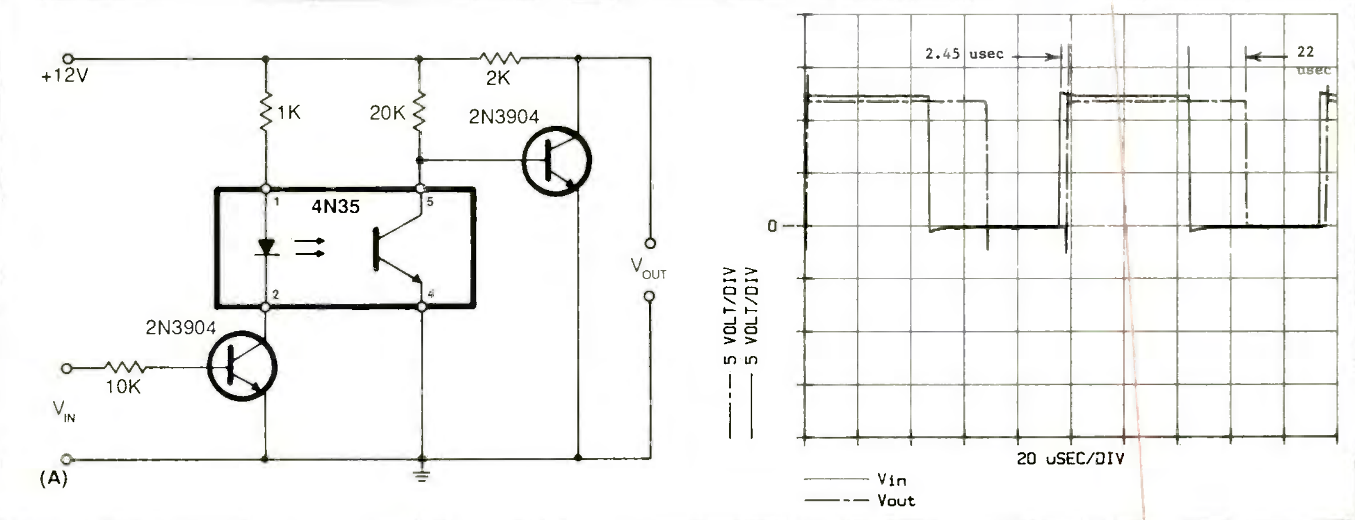

Fig. 7. Adding an output transistor to a 4N35 (A) increases switching-speed time over unassisted circuit (B).

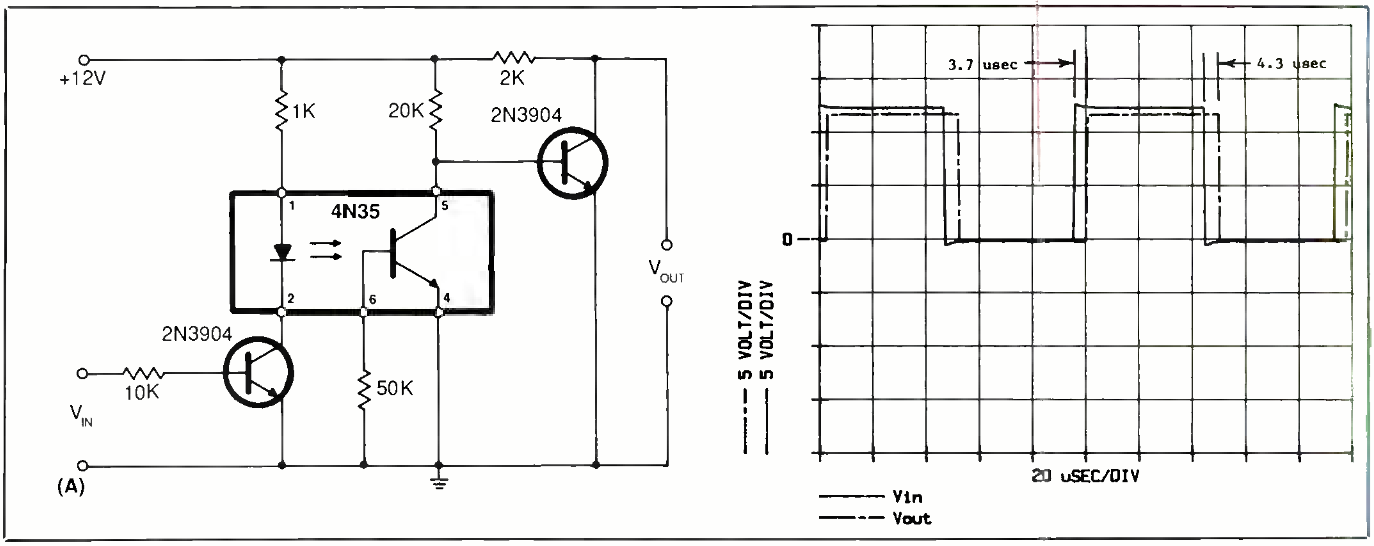

Fig. 8. A 50k-ohm resistor in base-emitter circuit (A) improves turn-on and turn-off times of 4N35 (B).

the base of the internal phototransistor, turning it on and shorting the base to the emitter of the 2N3904 output transistor. When this occurs, the output transistor turns off and produces a high condition at V_{out}.

When IR energy ceases to be generated by the LED, the phototransistor turns off. Now the base of the output transistor is pulled up by the 20,000-ohm collector load resistor and the output transistor turns on, causing a low output condition to appear at V_{out}.

As illustrated in Fig. 7(B), this extra output stage shortens switching time for turn-on down to 2.45 microseconds, a big difference from the 10.5-microsecond time of the unassisted Fig. 6(A) circuit. It also shortens the turn-off time down to 22 microseconds, compared to the 47-micro-second time for the unassisted circuit.

The reason for the improvement in turn-on response is that the load for the phototransistor inside the optoisolator is now 20,000 ohms, instead of the original 2,000 ohms. By reducing the amount of photon energy necessary to support the load current, more photocurrent can be used to charge the collector-base capacitor and get the phototransistor to turn on.

Turn-off time has been reduced because the phototransistor must now turn off to only 0.7 volt (instead of 0.1 volt) to send the output transistor into conduction and produce a low condition at V_{out}. Turn-off time is hindered somewhat, however, because the phototransistor's load has been reduced by the 20,000-ohm resistor. With this high-impedance load, the phototransistor's storage time is increased because its base region is flooded with excess photons and is free of electrons, a condition referred to as "hard saturation." The phototransistor will not even start to turn off until these extra electrons are used up.

The circuit in Fig. 8(A) is the same as that in Fig. 7(A), except that a 50,000-ohm resistor has now been added between the base and emitter of the phototransistor inside the 4N35. This resistor provides a path for the collector-base capacitor of the phototransistor to discharge and provides a dump for the excess electrons that caused the hard-saturation condition in the Fig. 8(A) circuit.

Addition of the 50,000-ohm resistor changes switching response time to 3.7 microseconds for turn-on and 4.3 microseconds for turn-off, as illustrated in Fig. 8(B). Turn-on time has now been increased by 1.25 microseconds over that for the Fig. 7(A) circuit because the sensitivity of the phototransistor has been spoiled somewhat by this resistor. Photon-generated current must now be used to turn on the output transistor, supply the 50,000-ohm load and charge the phototransistor's collector-base capacitor. Turn-off time has been improved by 17.7 microseconds, however. This improvement is well worth the slight loss in turn-on speed that was the penalty of adding the 50,000-ohm resistor.

In Fig. 9(A), a circuit has been added to the LED side of the 4N35 optoisolator to regain the lost phototransistor sensitivity during the turn-on period. This sensitivity is regained by "blasting" a current that is ten times the steady-state current into the internal LED for a sufficient period of time to get the phototransistor turned on.

The amount of time the current blast is present is set by the 0.01-mi-

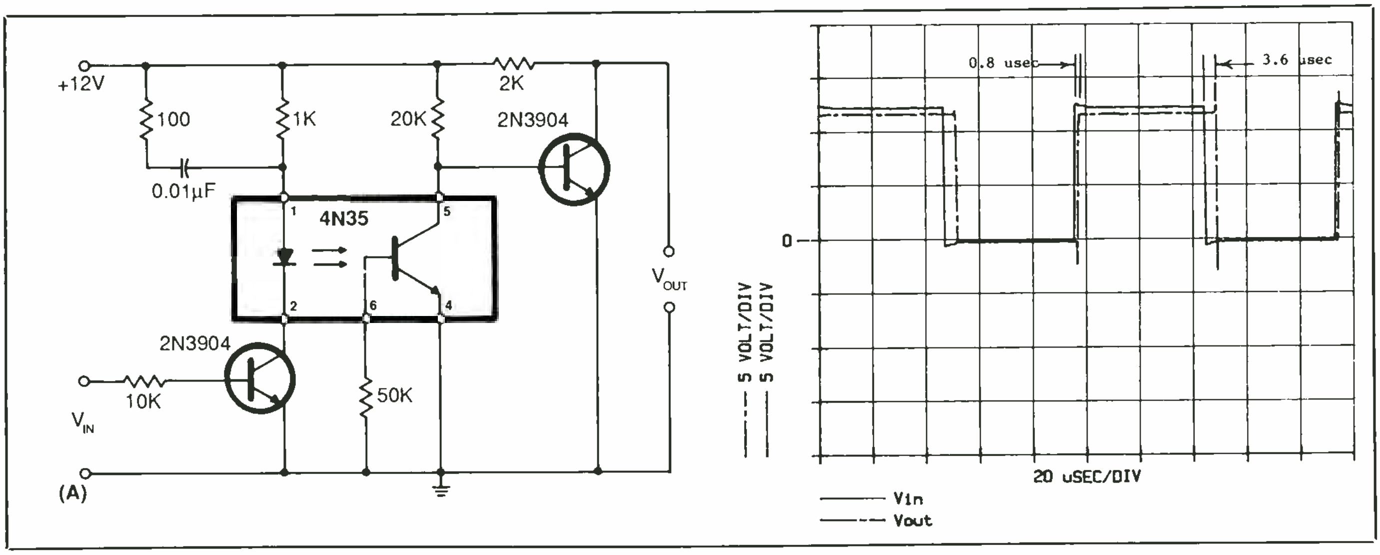

Fig. 9. Adding 100-ohm resistor and 0.01-microfarad capacitor to optoisolator's LED circuit (A) restores phototransistor's sensitivity that was lost with previous fix, as illustrated by the response curves in (B).

crofarad capacitor and 100-ohm resistor. With these values, blast time is 0.01 microfarad × 100 ohms = 1 microsecond. Care must be exercised to avoid exceeding the surge rating of the internal LED when using current blasting.

This change helped to restore the short turn-on time of the Fig. 8(A) circuit, as illustrated in Fig. 9(B). Turn-on time has now been reduced to 0.8 microsecond, while turn-off time is unaffected by this change.

Final Configuration

In optimizing the design of a fast-switching circuit built around a low-cost optoisolator, we come to the circuit shown in Fig. 10(A). In this circuit, a 1N5818 Schottky diode is shown connected across the terminals of the base and collector of the phototransistor inside the 4N35. This diode prevents the collector-base capacitance of the phototransistor from slowing down the device by limiting its charge and discharge range. The inherent capacitor can now charge only in the range from 0.7 to 0.5 volt.

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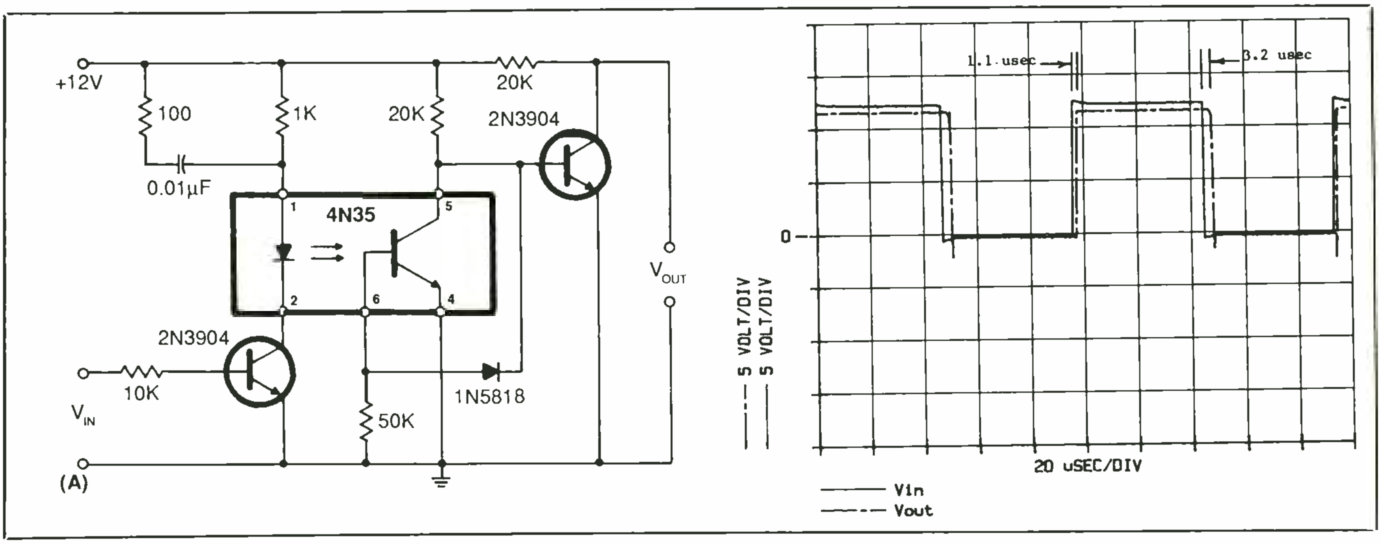

Fig. 10. Schottky diode between 4N35's collector and base (A) prevents collector-base capacitance from slowing down internal phototransistor, greatly improving turn-on and turn-off times (B) over those of unassisted circuit.

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The Schottky diode also prevents the transistor from going into a hard-saturation state. If the transistor turns on hard enough that the phototransistor's collector voltage falls more than 0.2 volt below the base potential of the phototransistor (about 0.7 volt), the Schottky diode turns on. At this point, all excess base electrons will be shunted away by the diode, leaving only enough electrons to keep the phototransistor slightly turned on. This prevents long delays before transistor turn-off initiates because of large amounts of electrons to be used up.

The bottom line with regard to the above is that the switching speed from the starting circuit to the final circuit is greatly reduced. Turn-on time started at 10.5 microseconds and has been reduced to 1.1 microseconds, for an almost 10-fold improvement. Turn-off time has been reduced from 44 microseconds to 3.2 microseconds, for a 14-fold improvement.

Although the fixes described here require some additional circuitry, total cost of the extra components needed is quite small when weighed against the improvements they bring. You should be able to incorporate these improvements at a cost of about $1.50 in addition to whatever you might have to pay for the low-cost optoisolator. A premium high-speed optoisolator, if available, may cost you $4.00 or more per device. The only real penalty you must pay to use a low-cost, commonly available optoisolator like the 4N35 in relatively high-speed (approximately 3.1-MHz, based on a 3.2-microsecond turn-on time) applications is an increase in circuit real estate. The Fig. 9 circuit shown here will provide adequate performance for all but the most demanding of high-switching-speed applications. Where very-high-speed switching is a critical requirement, you can always opt for a premium high-speed optoisolator. ME