ELECTRONICS NOTEBOOK

Using LEDs as Detectors

By Forrest M. Mims III

Light-emitting diodes can double as both emitters and detectors of light. This dual capability makes possible several unique applications. In this column, I will describe several applications for LEDs operated as detectors. First, however, let's review the background of devices that both emit and detect light.

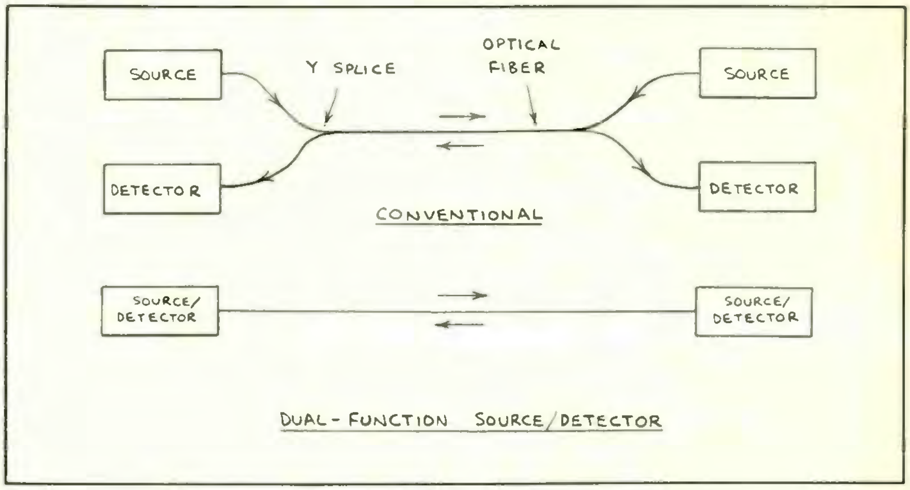

Fig. 1. Conventional and simplified bidirectional fiber links.

Detectors that Emit Light

A few months before graduating from high school in the spring of 1962, it occurred to me that semiconductors that detect light might also emit light. I decided to test this hypothesis by passing a current through a bulk semiconductor, a thin layer of cadmium-sulfide that formed the light-sensing region of a photoresistor.

When the current from a flashlight cell failed to stimulate the emission of photons, I decided more electromotive force might do the trick. Since I had been experimenting with a spark coil, I connected the CdS cell to the output leads of the spark coil and switched on the power. This time, the entire zig-zag pattern of CdS emitted a greenish glow. Of much more significance were tiny but bright spots of flickering green light.

Since CdS has a peak spectral response in the green range, I was convinced that the green emission was not merely a visual by-product of the high-voltage spark discharge but was what physicists call "recombination radiation." In other words, the green emission was the direct result of electrons within the CdS being stimulated to a higher-than-normal energy level by the high-voltage discharge. When the electrons resumed their normal levels (recombined), they emitted photons (radiation).

On November 6, 1966, I repeated this experiment with single-crystal platelets of cadmium-sulfide provided by the University of Colorado. The brittle, yellowish platelets produced green flashes that were significantly brighter than those produced in the earlier experiment, which I also repeated.

Earlier, on March 14, 1966, I conducted an experiment that eventually led to a confrontation with Bell Laboratories. In this experiment, I connected a surplus silicon solar cell to the output of a two-transistor audio-frequency oscillator. An identical cell was connected to the input of an audio amplifier. The first cell produced pulses of near-infrared radiation that were detected by the second cell.

This experiment demonstrated that half-duplex optical communications could be accomplished over a coaxial path with a single semiconductor device at either end of the link. When one solar cell was transmitting, the other would function as a receiver. Their roles would then be reversed for communication in the opposite direction.

Emitters that Detect Light

Most semiconductor pn junctions emit photons when forward biased. This is the principle that makes possible visible-light and near-infrared emitting diodes. The most efficient semiconductor light emitters are made from single-crystal alloys of gallium and arsenic (GaAs) and aluminum, gallium and arsenic (AlGaAs). But even silicon solar cells, as noted above, and both germanium and silicon diodes and transistors emit near-infrared radiation when forward biased.

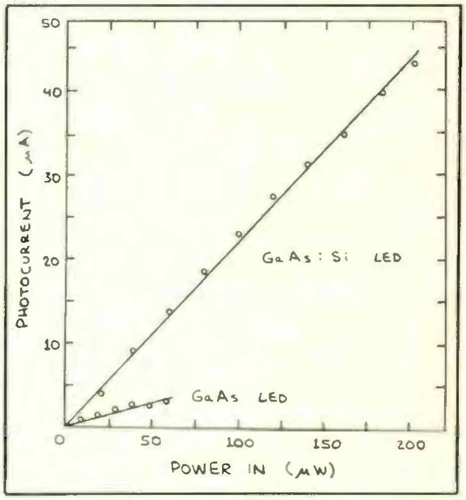

Fig. 2. Response of GaAs and GaAs:Si LEDs in detector mode.

The efficiency at which silicon and germanium pn junctions transform a current into an electromagnetic wave is considerably lower than that of diodes designed specifically for this purpose. Moreover, many diodes designed expressly as efficient photon generators function well as photon detectors.

In 1972, I conducted a series of experiments to determine if GaAs LEDs and lasers and GaAs:Si LEDs could double as detectors. The results of these experiments were quite successful. I also found that it is possible to transmit an information-carrying optical wave in both directions through a single optical fiber by placing a single LED at each end of the fiber. Previously proposed optical fiber communication links required an emitter and a detector at each end of a link made from either two fibers or a single fiber equipped with a "Y" splice at both ends. Figure 1 shows both methods.

In 1973, I sent Bell Laboratories a formal invention proposal that described several applications for dual-purpose emitter/detector devices. The proposal was reviewed by two scientists at Bell Labs, both of whom held the PhD. One wrote that it is not possible to design a practical device that functions as both an emitter and a detector. His supervisor concluded that, "I think it extremely unlikely that systems considerations would permit a single device to operate as both a source and detector. Certainly all of our present thinking has been along the lines of separate fibers for transmitting and receiving." My proposal was rejected.

I related some of the details of what happened next in *Siliconnections: Coming of Age in the Electronic Era* (McGraw-Hill, 1986). Briefly, after Bell Labs rejected the proposal, I developed a magazine construction project titled "Communicate Over Light Beams With the First Single-LED Transceiver" (*Popular Electronics*, March 1974). This article concluded that the device's ". . . fiber-optic mode of operation is a precursor of what telephone systems of the future are likely to resemble."

In the fall of 1979, Bell Labs announced that it had also developed a new kind of single-LED transceiver, an optical telephone that *Electronics* claimed would ". . . establish AT&T as the No. 1 provider of wideband services to home and industry" (October 25, 1979). *Business Week* described the new phone as ". . . so radically different it may eventually transform American Telephone and Telegraph Co. and the entire telephone industry with profound effects on data communications, cable television, and every phone user . . . and dramatically alter the basic nature of the phone network" (December 4, 1978).

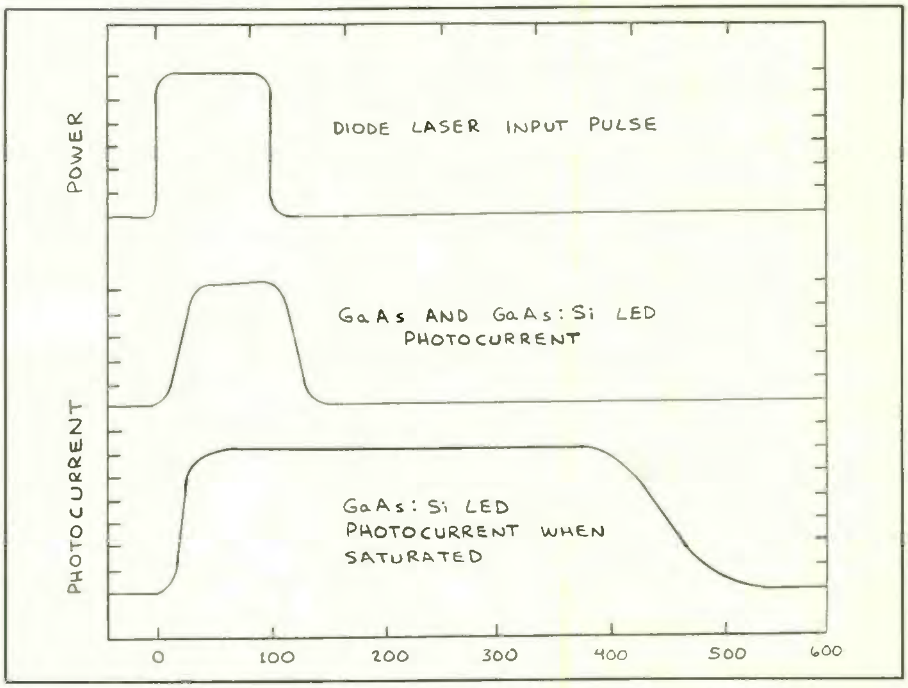

Fig. 3. Response times (nanoseconds) of LEDs in photodetector mode.

When I approached Bell Labs about its apparent use of the invention I had submitted to them, they refused to honor our 1973 agreement that, should they desire to make use of my proposal, they would first ". . . discuss the matter . . . in an effort to arrive at an agreement that is mutually satisfactory." Following six months of unsuccessful negotiations, I filed suit against Bell Labs. The matter was settled out of court in my favor in December 1980.

During this litigation, Bell Labs abandoned at least one U.S. patent application that in part claimed precisely what I had submitted to them in 1973. Furthermore, an extensive search of the prior art by Bell Labs revealed that Jean Claude Chaimowicz had applied for an English patent (No. 1,101,223) in 1965 that proposed a two-way free-space optical communications system using a single dual-function semiconductor at each end of the link. Other early work was performed at IBM from 1969 to 1972, including one-way links using fiber optics.

Some Experimental Results

It's important to realize that off-the-shelf LEDs often function well as optical transceivers. I made some measurements of the performance of commercial LEDs operated as detectors that will give you a good idea of their sensitivity.

"External quantum efficiency" is an important measure of a detector's performance. A detector generates a photocurrent when illuminated by a light source. The external quantum efficiency of the device is the ratio of the number of photocurrent electrons to the number of photons striking the detector during a given period of time. Thus, if each photon generates an electron, the quantum efficiency is 1 (or 100 percent). If two photons are required to generate an electron, the efficiency falls to 0.5 (or 50 percent), and so forth.

With the help of a calibrated silicon

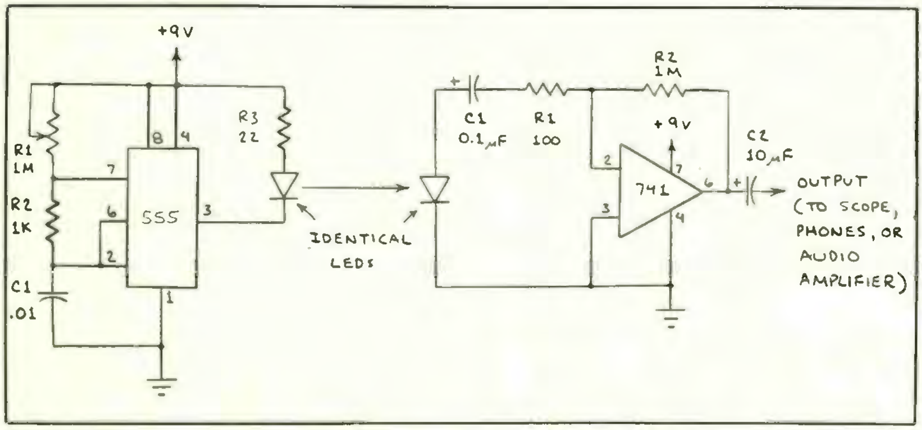

Fig. 4. A simple LED-LED demonstration circuit.

photodiode, I measured the external quantum efficiency of several GaAs and GaAs:Si LEDs. In each case, the LED connected as a detector was illuminated by radiation from an identical LED. This is because an LED operated as a detector responds best to the band of wavelengths at or slightly below the band of wavelengths it emits when operated as an emitter.

A General Electric SSL-54 GaAs LED with a peak emission wavelength of 900 nm gave a quantum efficiency of 8.8 percent when operated as a detector. A GE SSL-55 GaAs:Si LED with a peak emission wavelength of 940 nm gave a quantum efficiency of 26 percent in the detector mode. The external quantum efficiency of commercial silicon photodiodes ranges from 50 to 70 percent. Though the LEDs I measured are not nearly this efficient, their performance is more than adequate for many practical applications.

I also measured the photocurrent generated by both LEDs in response to an increasing level of illumination from similar LEDs. As can be seen in Fig. 2, both diodes exhibited a linear response over the range of applied radiant power.

Optical communications is an important application for LEDs operated as both detectors and emitters. Therefore, I measured the response of the LEDs cited above to fast-risetime (1-nanosecond) pulses from a GaAs semiconductor laser diode. Both LEDs were connected across a 50-ohm load resistor. The current through the resistor was monitored with an oscilloscope. As shown in Fig. 3, both LEDs exhibited rise and fall times of around 25 nanoseconds (10- to 90-percent points).

Note in Fig. 3 that the GaAs:Si LED exhibited a considerably increased fall time when the incoming radiation exceeded the device's saturation point, at which increasing radiation fails to generate a greater photocurrent. Well above saturation, the 100-nanosecond-wide pulse from the laser diode was stretched to 450 nanoseconds. This effect is probably related to the fact that, when operated as emitters, GaAs:Si LEDs exhibit much slower rise and fall times than do GaAs LEDs. Of course, what this means is that GaAs:Si LEDs are not as suitable for wide-bandwidth links as are GaAs LEDs.

During the past five years or so, highly efficient red and near-infrared emitting AlGaAs LEDs have become widely available. Though I have not quantified the performance of AlGaAs LEDs in the detector mode, I have had excellent results using both red and near-infrared AlGaAs LEDs as detectors. AlGaAs LEDs used as detectors should be paired with similar AlGaAs LEDs. Thus a super-bright red AlGaAs LED will detect the light emitted by a similar LED much better than the radiation emitted by a near-infrared AlGaAs LED.

Simple LED-LED Test Circuits

There are several ways to determine if a pair of similar LEDs will work in an optical transceiver application. The most straightforward is to connect one LED to a current meter and expose it to radiation emitted by the second LED. This is essentially how I made the quantum efficiency measurements mentioned above.

When performing such tests, it's helpful to compare the performance of LEDs to that of conventional detectors. For example, the receiving LED can be replaced by a silicon photodiode or solar cell. For a fair comparison, it is essential to compensate for the sensitive surface area of the detectors being compared. The simplest way to do this is to form a small hole in a sheet of aluminum foil and expose all the detectors under test through this hole.

Since LEDs have a much smaller sensitive region than a solar cell, this procedure can be simplified by making a hole in the foil so that it has the same dimensions as the LED's chip. The LEDs can then be tested without the external aperture, while large-area detectors, such as solar cells, can be tested with the aperture.

Figure 4 shows a simple arrangement that will allow you to quickly determine if a particular pair of LEDs will work in a bidirectional audio-frequency lightwave link. In operation, the transmitter LED sends a stream of pulses to the receiver LED. The photocurrent from the receiver LED is amplified, and the magnitude of the audio tone provides a rough indication of whether or not the selected pair of LEDs will function in a practical lightwave link.

The Fig. 4 transmitter is a straightforward 555 pulse generator. Potentiometer *R1* controls the pulse repetition rate. Though the simple receiver shown works well, you can connect the receiver LED directly to the input of a commercial audio amplifier.

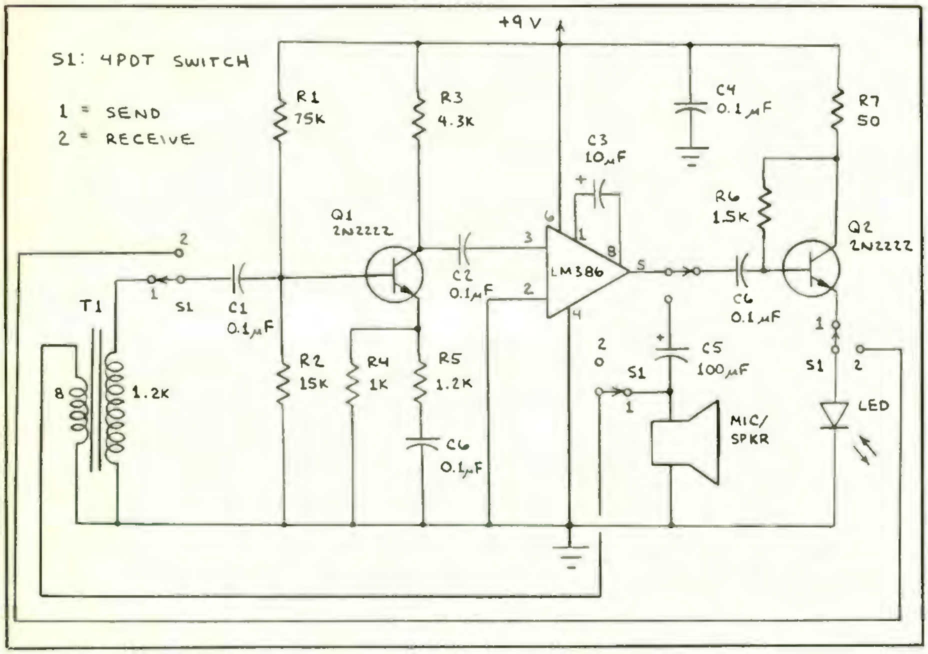

Fig. 5. Lightwave voice communicator with LED source/detector.

Remember that the Fig. 4 arrangement provides only a rough indication of an LED's performance as a detector. For more precise information, it's necessary to make measurements as described above.

A LED-LED Transceiver

Since 1973, I have built a number of working lightwave transceivers that incorporate a single LED as a dual-function source and detector of optical radiation. These transceivers have been operated through the atmosphere over ranges of hundreds of feet and through optical fibers over similar distances.

Figure 5 is the schematic diagram of one of these systems. You can use this circuit to demonstrate that the concept of a lightwave transceiver in which a single LED doubles as a source and a detector is indeed a practical proposition. Or you can adapt the circuit to a practical system.

Note in Fig. 5 that a standard 8-ohm speaker functions as both a microphone and a speaker. Setting *S1* to position 1 connects the speaker to the 8-ohm side of audio transformer *T1*. Speech directed into the cone of the speaker generates a small current that is coupled into *Q1* via *T1* and *C1*. The amplified signal is then coupled through *C2* into the LM386 audio power amplifier chip. The output from the LM386 is then coupled into LED driver *Q2*, which controls the current flowing through the LED. Hence, speech directed into the speaker's cone is transformed into an amplitude-modulated lightwave by the LED.

Setting *S1* to position 2 connects the speaker to function as a speaker instead of as a microphone, and the LED is connected to *Q1* via *C1*. Lightwaves striking the LED's junction generate a photocurrent that is amplified by *Q1* and passed through *C2* to the LM386 power amplifier. The output of the LM386 is then passed to the speaker via *C5*.

A pair of the Fig. 5 circuits can be used for half-duplex, bidirectional communication through the atmosphere or through a single optical fiber. If you have built and used lightwave communication systems designed to operate through the atmosphere, you can appreciate the advantage of having a single lens rather than two lenses at either end of the link. This greatly simplifies alignment of a pair of transceivers.

For best results, the LED should be an AlGaAs near-infrared or super-bright red device. Near-infrared LEDs will provide a covert communications link, but alignment is more difficult than when visible LEDs are used.

Various kinds of optical fiber termination devices are available for interfacing fibers and LEDs. Alternatively, you can attach a fiber directly to an LED. One way to do this is illustrated in Fig. 6. Here a small hole is bored into the end of an epoxy-encapsulated LED. You can form the hole with a small drill or a hot needle. In either case, it's important to avoid damaging the very small bonding wire that connects one of the LED's leads to the top of the chip.

After forming the hole, dip the end of the fiber into clear epoxy and insert it in the hole. The epoxy secures the fiber in place and provides refractive index matching between the end of the fiber and the roughened end of the bored hole.

You can use plastic optical fiber if the LED is a visible red emitter. Plastic fiber is easy to cut with a sharp safety knife or razor blade.

Silica and glass fibers have much lower characteristic attenuation than plastic fibers do, and they can be used with both red and near-infrared emitting LEDs. These fibers must be cleaved to provide a perfectly flat end. One way to cleave a glass or silica fiber is to lightly score it with a carbide blade. First, pull the fiber across a curved surface, such as a plastic 33-mm film container. Then lightly pull the carbide blade across the desired cleavage point. The fiber should almost immediately pop apart.

Examine the end of the fiber with a record player stylus magnifier. When light is shining through the opposite end of the fiber, a properly cleaved end will be a brightly glowing circle. A half-moon of glowing light indicates an imperfect cleave, in which case, you should try again.

Caution: You *must* wear protective glasses when cleaving glass and silica fibers since small slivers broken off during cleaving might fly into your eye. Small remnants of fiber are like invisible splinters that can cause painful injuries. Collect fiber scraps with the mastic side of a piece of masking tape and discard them in a safe place.

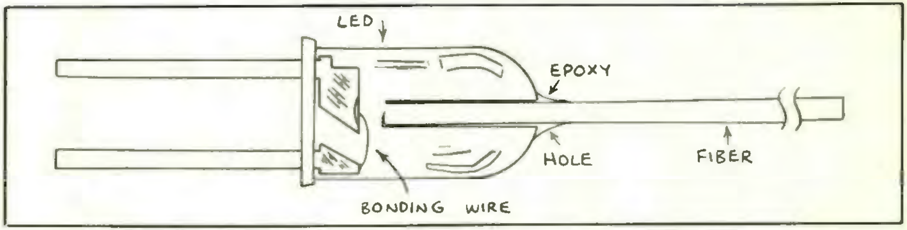

Fig. 6. How to mate an optical fiber to an encapsulated LED.

Going Further

The conclusions of the scientists at Bell Labs in 1973 notwithstanding, LEDs *can* indeed double as both emitters and detectors in practical lightwave communication links. For example, I have used a pair of circuits similar to that shown schematically in Fig. 5 and equipped with near-infrared LEDs to transmit voice in both directions through a 200-meter silica fiber. In February 1980, I demonstrated this system at the site in Washington, D.C., where Alexander Graham Bell first demonstrated voice communication over a beam of reflected sunlight exactly 100 years earlier. Besides my wife and me, present were representatives of the Smithsonian Institution, the National Geographic Society and, despite their ongoing legal battle, Bell Laboratories.

For additional information about lightwave communications and LEDs that function as both emitters and detectors, see *The Forrest Mims Circuit Scrapbook* (McGraw-Hill, 1983) and *Forrest Mims' Circuit Scrapbook II* (Howard W. Sams, 1987). In *A Practical Introduction to Lightwave Communications* (Howard W. Sams, 1982), which is out of print but still available from some libraries, I discuss lightwave communications in great detail. **ME**