How to Detect Ultraviolet, Visible Light and Infrared Radiation

By Forrest M. Mims III

Even though many different kinds of light detectors are available, most of us routinely use only phototransistors and photoresistors for the majority of our light-detection applications. This leaves out many kinds of light detectors that may work much better.

This is the first of several columns in which I plan to introduce each of the most-important classes of light detectors and describe how they are used. I'll also present some circuits you can try with various detectors. First, however, let's devote some time to defining light and to looking at the first light detector and some of the many applications that light detectors have since made possible.

Light Defined

There isn't enough space here to include a full discussion about the physics of the nature of light. But it is important to define which wavelengths of the electromagnetic spectrum are generally considered to be light.

Light is usually considered to be those wavelengths of the electromagnetic spectrum that are visible to the human eye. By this definition, light is restricted to the wavelengths that form the colors of the rainbow. These wavelengths are usually said to range from about 380, nanometers on the blue end to about 780 nanometers on the red end of the spectrum.

Actually, the boundaries that separate visible and invisible light are rather fuzzy. Depending on the intensity of the light and its contrast with the background, many people can see beyond 380 nanometers on the blue end of the spectrum and beyond 780 nanometers on the red end. For example, most people can easily see the 780-nanometer radiation emitted by the diode laser in a compact-disc player. People who have had the lens of an eye removed during cataract surgery can see down to 320 nanometers.

Invisible electromagnetic radiation between 200 nanometers and the lower limit of visible blue light is called the ultraviolet spectrum. Sometimes, ultraviolet radiation is called "black light."

Invisible electromagnetic radiation beyond visible red light and out to 1,000 micrometers is known as the infrared spectrum. Since the infrared spectrum is so wide, it's usually subdivided into three regions. Wavelengths out to 1.5 micrometers make up the near-infrared spectrum. Wavelengths between 1.51 and 6 micrometers make up the middle-infrared region. Finally, wavelengths between 6 and 1,000 micrometers are perceived as heat by the human body. (*All* electromagnetic radiation causes at least some increase in the temperature of objects it strikes. More about this later.)

Shown in Fig. 1 are the relationships of ultraviolet, visible and infrared radiation to the remainder of the electromagnetic spectrum. Often, the definition of light is extended to include some or all of the ultraviolet and infrared wavelengths. Many kinds of light detectors can detect wavelengths across the ultraviolet/visible or visible/infrared regions of the spectrum. Therefore, for the purpose of this column, the broader definition of light will be used.

Blackbody Radiation

Electromagnetic radiation is emitted by any object whose temperature is greater than that of absolute zero (0 degree Kelvin or −273.18 degrees Celsius). This is known as "blackbody radiation." Since

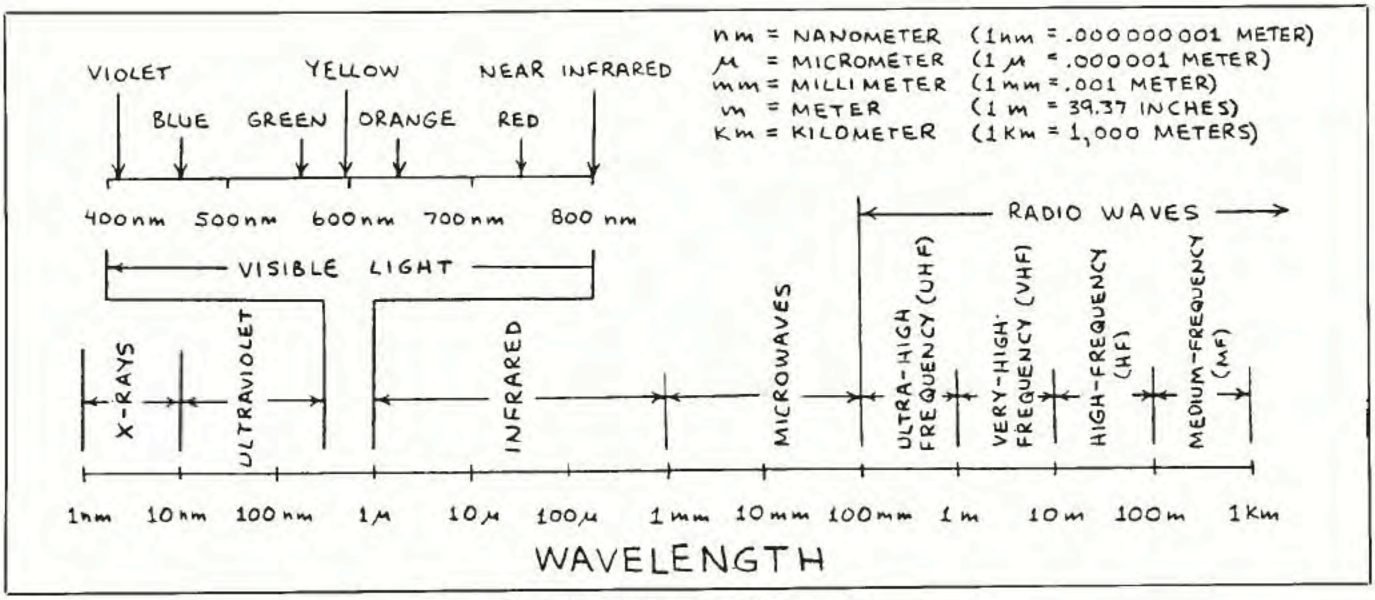


Fig. 1. The electromagnetic spectrum.

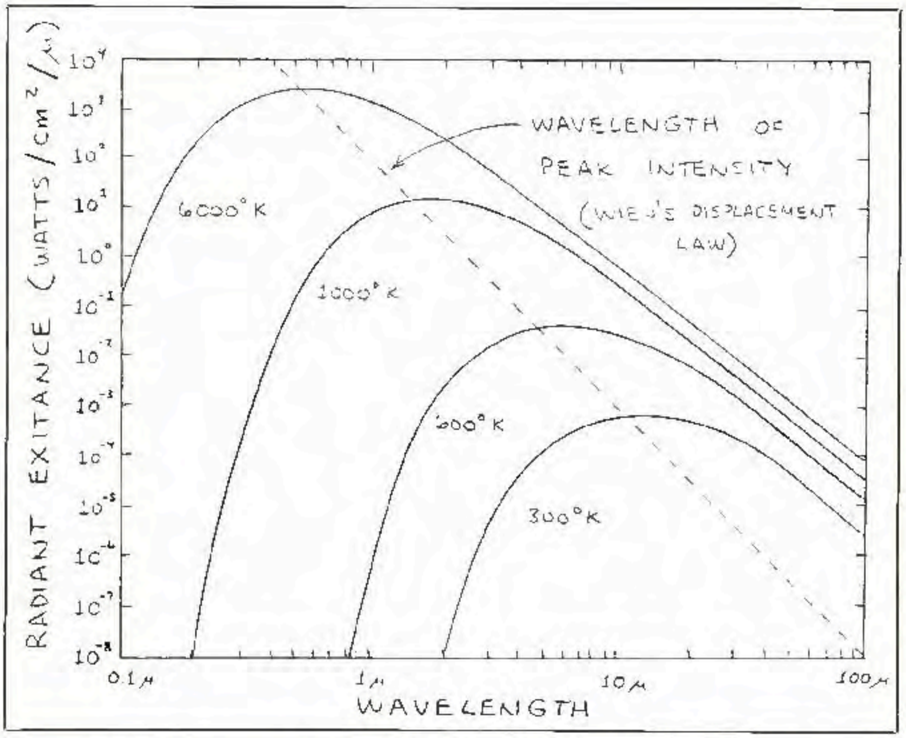


Fig. 2. Peak spectral existence of a blackbody at various temperatures.

nothing is known to be at a temperature of absolute zero, everything is a blackbody radiator.

The peak wavelength of the blackbody radiation emitted by an object is directly related to the temperature of that object. The blackbody radiation of an object whose temperature is less than about 1,725 degrees Celsius falls predominantly in the infrared portion of the spectrum. While the page you are reading is an excellent reflector of visible light, it is much too cool to emit visible blackbody radiation. If this page is at room temperature (300 degrees Kelvin), it's emitting blackbody radiation that has a peak wavelength of around 9.66 micrometers.

The peak spectral wavelength emitted by a blackbody at a given temperature is given by Wien's displacement law, which states that Wavelength = 2,898/temperature in degrees Kelvin. For example, if your body temperature is 310 degrees Kelvin, the peak blackbody radiation emitted by it has a wavelength of 2,898/310 degrees, or 9.35 micrometers. Since the temperature at the surface of your skin is is actually less than 310 degrees Kelvin, your blackbody radiation is somewhat greater than 9.35 micrometers.

Graphed in Fig. 2 is the radiation emitted by a blackbody at a range of temperatures. The curve for a blackbody at 6,000 degrees Kelvin approximates the radiation from the sun outside the Earth's atmosphere. The straight line that connects the peak emission wavelengths follows Wien's displacement law.

Wien's displacement law works both ways. For example, if the peak spectral wavelength of a glowing ladle of molten metal can be measured, the temperature of the metal can be calculated using Wien's displacement law. The same procedure can be used to determine the temperature of the filament in an incandescent lamp when current is flowing through it. The *color temperature* of the light source is the temperature at which a hot blackbody must be maintained to produce a spectrum of light that matches that of the light source.

First Light Detector

According to Genesis, God invented both light and the first light detectors. Biological light detectors remained the only ones available until 1873. In that year, Willoughby Smith was working with multiple-megohm resistors made from crystalline selenium that he had designed to test a submerged transoceanic cable. His assistant, a Mr. May, discovered that the resistance of the selenium resistors was greatly reduced when the devices were exposed to sunlight.

Smith performed some experiments with selenium light detectors and his results created great interest in scientific circles. Soon, other scientists confirmed what May and Smith had discovered. Within a few years, it was learned that selenium was most sensitive to greenish-yellow light and that a selenium detector could function as a sun-powered battery.

Early experiments with selenium light detectors were performed by connecting the detector in series with a battery and a galvanometer. In 1878, Alexander Graham Bell proposed substituting a telephone receiver for the galvanometer so that changes in light intensity could be converted into audible sound. The eventual result was his invention of the photophone, the first lightwave communication system.

Applications

Circuits that detect light have become increasingly important in electronics. Most cameras include built-in light sensors. At the receiving end of every infrared remote-control unit is a detector. Night lights and security lights are switched on and off by a light sensor. Many telephone conversations are transformed into flashes of light that are sent though optical fibers and received by sensitive light detectors. Sensitive detectors connected to fiber-optic sensors detect liquid level, particles displacement and vibration.

ELECTRONICS NOTEBOOK...

Light detectors are used to detect fire, match colors and measure ultraviolet radiation. They are used to receive the beams of lasers and LEDs in break-beam intrusion-detection systems. Light detectors read the bar codes on labels, and they detect the laser beam deflected from the surfaces of compact discs.

Many new applications are made possible by placing two light detectors side by side in the same case or package. This forms what is known as a dual detector. In a typical application, each half of the detector is connected to one input of a difference amplifier and the dual detector package is placed at the focal point of a lens or parabolic reflector.

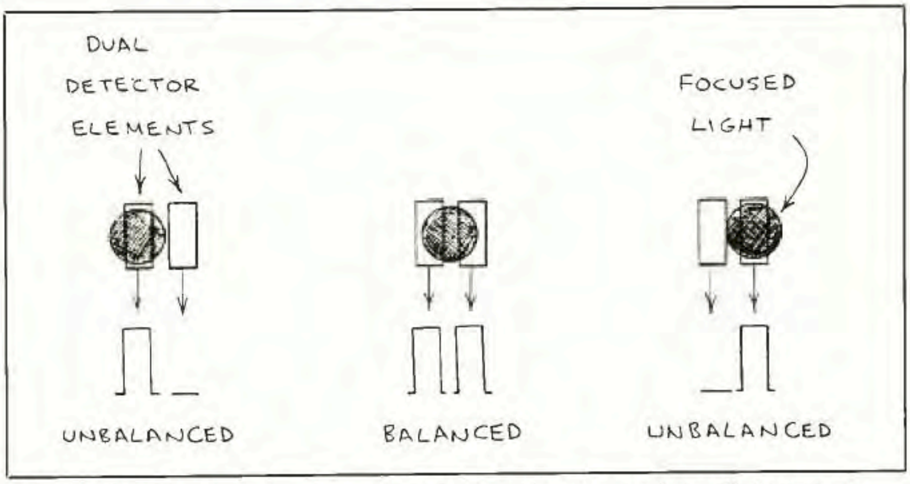


Fig. 3. These drawings show how a dual detector detects a moving radiation source.

Normally, as shown in Fig. 3, both detectors receive the same amount of illumination; hence, the output of the two detectors is balanced. If something that alters the amount of light being received by one half of the dual detector moves across the field of view of the detector, one detector will generate a greater output than the other. When this occurs, a voltage appears at the output of the difference amplifier.

Dual detectors are especially useful for detecting the flickering flames of a fire. They're also widely used to detect moving objects and even people and animals. All these applications are possible by using detectors that respond primarily to either visible light or to infrared radiation.

The above are only some of the many —almost limitless number of—applications for light detectors. I haven't even listed applications for position-sensitive detectors, detector arrays and image detectors used in television cameras.

Detector Specifications

Light detectors can be characterized by many different specifications. The most important of these are response time, sensitivity and noise.

Many applications can tolerate very-slow response times. Who cares, for example, if a night light switches on in a few milliseconds or a few nanoseconds? Photoresistors are very slow to respond, but their excellent sensitivity makes them an ideal choice for this application.

Other applications require very-fast response times. Optical-fiber communication systems are a good example, since most such systems transform voice signals into pulses of light. Semiconductor junction photodiodes have a very-fast response time, making them ideally suited to this application.

Generally speaking, junction detectors with a small active surface are faster than those with a large active surface. This is because smaller detectors have less junction capacitance than do larger detectors.

The sensitivity of a detector is a measure of how well it responds to light at a particular wavelength. For example, a typical silicon photodiode has a sensitivity of about 0.5 ampere per watt to light that has a wavelength of about 900 nanometers. In other words, a photodiode that has this sensitivity will generate a current of about 0.5 milliampere when it is illuminated by 1.0 milliwatt of radiation at a wavelength of 900 nanometers.

Sensitivity of some detectors varies with previous exposures to light. For example, the resistance of a photoresistor varies with the light striking the active surface. After the light source is removed, the photoresistor's resistance may not return completely to its normal or dark value for some time. This is called the "light-history" or "memory" effect.

Like diodes and resistors, light detectors generate internal noise. The noise of a light detector is often specified in terms of *noise equivalent power* or *NEP*. The NEP of a detector is the level of light that matches the detector's inherent noise level. In terms of signal-to-noise ratio, a detector's NEP is that level of light that gives an SNR (S/N ratio) of 1.

Keep in mind that detector specifications apply to the detector as it is purchased. For example, so-called blue-enhanced silicon photodiodes can be used to detect ultraviolet radiation. But ultraviolet radiation is highly attenuated by most kinds of glass and plastic. Therefore, the detector will not meet its specifications if it is placed behind a window or lens that does not transmit the ultraviolet.

The dozens of different types of light detectors can be divided into two broad categories: thermal detectors and photodetectors. Thermal detectors indirectly detect the presence of light by measuring either the temperature increase or some effect of the temperature increase that occurs when light strikes a temperature-sensitive element. Photodetectors detect light directly by the photoelectric effect.

There are many differences between thermal and photoelectric detectors, but the most important is spectral response. Thermal detectors have a spectral response that is virtually flat from the deep ultraviolet to the far infrared. Photoelectric detectors, on the other hand, have a much narrower spectral response.

Thermal Detectors

Since thermal detectors respond to a temperature increase, a common misconception it that they detect only infrared radiation. Actually, as noted above, thermal detectors can detect ultraviolet and visible wavelengths as well, because all wavelengths of light can cause a temperature increase. That's why the blue-green beam from an argon laser I was once using virtually instantly ignited a black cloth that shielded some equipment from ambient light.

The temperature-sensitive resistor or bolometer was among the first thermal detectors. The thermistor is a semiconductor bolometer.

A thermopneumatic or Golay cell is a small gas-filled chamber. A thin film on one wall of the chamber bulges outward when the internal gas expands on being warmed by optical or IR radiation. Displacement of the film is detected by a simple interferometric technique in which Newton's rings are formed.

In 1938, an array of 61 thermopneumatic cells was used to detect aircraft more than 20 kilometers away. The cells were mounted at the focal point of a 1.5-meter military searchlight mirror. A single cell could detect an aircraft. Movement of the aircraft could be detected while observing changes in the Newton's rings on the individual detectors.

Another early kind of thermal detector is the thermocouple, which is the junction of two dissimilar metals that produce a voltage when heated. The thermopile is an array of thermocouples that provides more output voltage than is possible with a single thermocouple.

Finally, there is the pyroelectric thermal detector. One such detector is made from lithium tantalate, an asymmetrical, non-conducting crystal. Electrodes are applied to both sides of the crystal to form a capacitor. The internal electrical field of the crystal appears across the electrodes of the capacitor. When the crystal is illuminated, the charge on the capacitor is almost instantly altered.

Besides lithium tantalate, pyroelectric detectors are made from ceramics like lead zirconate titanate. They are also made from piezoelectric film.

Comparisons

Thermopiles and pyroelectric detectors are by far the most important kinds of thermal detectors. Miniature thermopiles, which can be purchased for as little as $50, are several times more expensive than some inexpensive pyroelectric detectors. On the other hand, thermopiles are much easier to use. Since they generate a voltage, they can be used with simple high-gain op-amp circuitry.

Since pyroelectric detectors are electrically equivalent to tiny capacitors, they must be connected to FET-input amplifiers that have a very-high input impedance. Otherwise, the minuscule charge on the detector will be drained away before it can be measured.

Pyroelectric detectors are very sensitive and have a much faster response time than thermopiles. But it's important that you realize that pyroelectric detectors respond only to *changes* in incident radiation. Thermopiles, on the other hand, generate a continuous output current when illuminated by a light source.

What does the foregoing mean in practice? Shine a flashlight on a pyroelectric detector, and it will generate an output pulse. Remove the light, and it will generate a second pulse. Repeat this experiment with a thermopile, and it will generate a continuous current for the entire time it is illuminated.

Pyroelectric detectors can easily detect moving sources of ultraviolet, visible-light or infrared radiation if the detector is placed at the focal point of a lens or reflector. For steady sources that do not move, a chopper wheel can interrupt the radiation that strikes the detector.

As noted above, the spectral response of thermal detectors is virtually flat. That's because their spectral response is dependent solely on the absorption properties of the black soot or paint used to

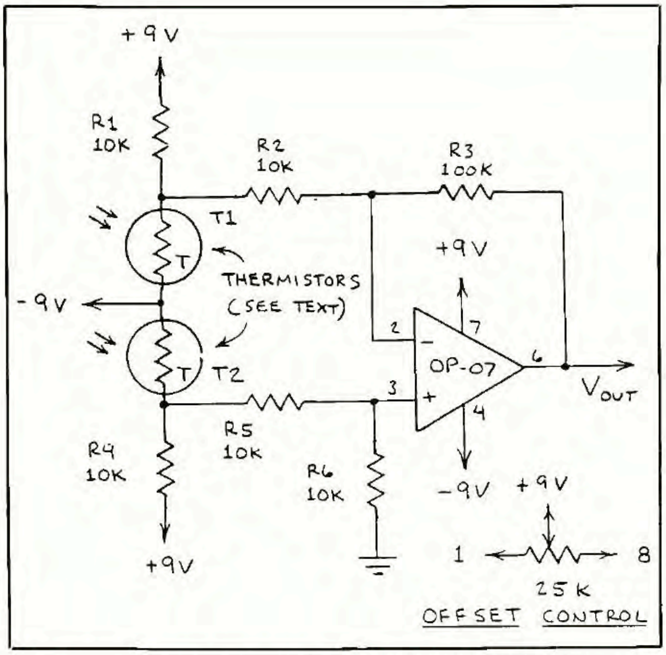
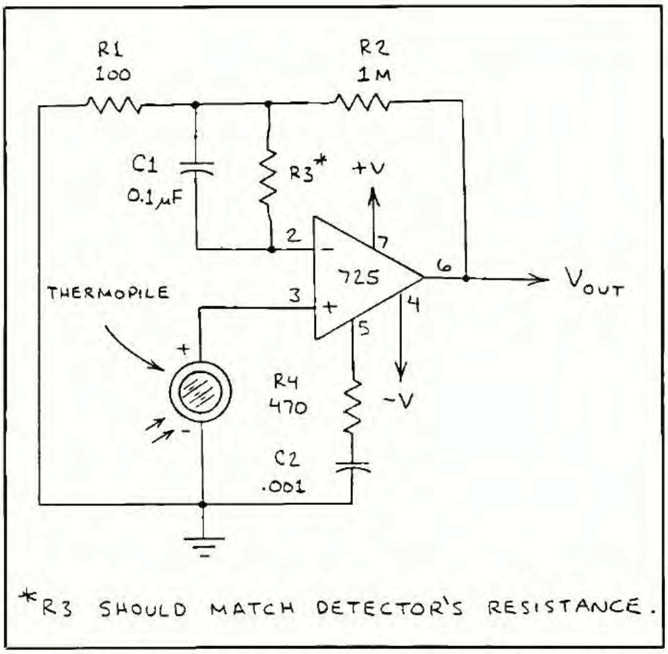


Fig. 4. A sensitive thermal detector made with thermistors.



*R3 SHOULD MATCH DETECTOR'S RESISTANCE.

Fig. 5. A precision amplifier for a miniature thermopile.

coat the detector's active surface. The spectral response can be changed by using filters or different kinds of window materials that double as filters.

Potassium bromide (KBr), a common window material for thermal detectors, has excellent transmission properties from the ultraviolet out to beyond 35 micrometers. Quartz or silica is used when ultraviolet and visible wavelengths are being detected. Germanium is used to block these wavelengths in favor of a band between 2 and around 20 micrometers. The infrared energy emitted by you and me peaks at around 10 micrometers, thereby making germanium a suitable window material when human beings are being detected.

Both pyroelectric and thermopile detectors are available with either single or dual elements for detection of flickering flames or moving objects, as above.

Briefly reviewing, the two outputs from the dual detector are connected to the inputs of a difference amplifier, and the detector is placed at the focal point of a lens or mirror. When both elements are equally illuminated, the output of the amplifier is zero. When one element receives more radiation than the other does, the output of the amplifier swings positive or negative. The direction of output swing is determined by which element is warmer than the other.

Experimenting With Thermistor Detectors

I described thermistors in some detail in my May 1989 "Electronics Notebook" column. The main emphasis of that column was the use of thermistors as indicators of temperature change. Several application circuits were provided.

You can make a simple thermistor detector from a blackened thermistor by attaching a thermistor to a small piece of metal that is coated with soot or black paint. While this arrangement will detect light, it will also respond to changes in the temperature of the surrounding air. Therefore, it must be used when the temperature of the surrounding air is very stable. Alternatively, or it must be shielded from air currents.

You can greatly increase the sensitivity of a thermistor by mounting it at the focal point of a flashlight reflector. You can prevent air currents from producing false signals by covering the reflector with a polyethylene film, which is a good transmitter of infrared radiation.

Temperature effects can be canceled out by using two thermistors, one of which is shielded from the light being measured. The outputs from the sensors then go to a difference amplifier.

Figure 4, for example, shows one way to connect two thermistors to a difference amplifier. The thermistors are Radio Shack Cat. No. 271-110 devices. This readily available thermistor has a resistance that ranges from 329.2 kilohms at − 50 degrees Celsius to 758 ohms at + 110 degrees Celsius. Many other thermistors will also work in this circuit.

I used an OP-07 precision operational amplifier for the Fig. 4 circuit, but other high-quality op amps will work equally well. Connect the amplifier's output to an analog multimeter set for a full-scale indication of a few volts or so. Feedback resistor *R3* should have a resistance of about 20,000 to 30,000 ohms for initial tests. Adjust the OFFSET CONTROL so that the meter's pointer is near the middle of the scale. The pointer will move toward the positive end of the scale when you touch thermistor *T1* and to the negative end when you touch thermistor *T2*.

You can increase the sensitivity of the Fig. 4 circuit by increasing the value of *R3*. First, place a short piece of clear plastic tubing over the two thermistors to keep away stray air currents. Then adjust the value of *R3*. The meter's pointer will tend to swing wildly when you adjust the OFFSET CONTROL. Therefore, use a high meter range setting at first to avoid damaging the analog movement.

When you finally balance the circuit, it will be extremely sensitive. Pointing the 1-milliwatt beam from a helium-neon laser at one thermistor will cause a pointer deflection of tens of millivolts. A flashlight will cause a much greater deflection.

Experimenting With Thermopile Detectors

You can perform many interesting experiments in ultraviolet, visible-light and infrared detection with a thermopile detector. If your budget is limited, you can attempt to make your own thermocouple from two dissimilar metal wires. Thermocouple wire is available from many sources. The Electronic Goldmine (P.O. Box 5408, Scottsdale, AZ 85261) sells a 2-inch length of thermocouple wire for 49 cents (specify Cat. No. S2009). Omega Engineering, Inc. (P.O. Box 2669, Stamford, CT 06906) stocks every imaginable kind of thermocouple and raw thermocouple wire.

If you can spare around $50, your best bet is to purchase a miniature thermopile detector. Dexter Research Center, Inc. (7300 Huron River Dr., Dexter, MI 48130) is a major manufacturer of thermopile detectors. The company makes a dozen or so single- and dual-element multi-junction detectors, most of which are priced at $50 or $60 each. Optional window materials and filters are available for an additional $4 to $10.

While I have not yet experimented with a miniature thermopile detector made by Dexter Research, I have worked with a Model C1 miniature thermopile made by Sensors, Inc. Unfortunately, this company no longer makes miniature thermopile detectors, but the Model C1's design and specifications are similar to those of some of the thermopiles made by Dexter Research.

The Model C1 thermopile features 12 miniature thermocouples deposited on a substrate and connected together to form a thermopile. The active region of the thermopile is coated with black paint or soot and is installed in a TO-5 transistor case. The case is fitted with a potassium bromide window that transmits optical wavelengths ranging from 250 nanometers in the ultraviolet to more than 35 micrometers in the infrared.

Thermopiles made by Dexter Research that have specifications similar to those of the Model C1 include the Model M5 with 10 junctions and the Model 1M with 15 junctions.

Figure 5 is adapted from a circuit recommended by Dexter Research for amplifying the signal from its thermopile detectors. You can use a common 741 op amp in this circuit, but you'll obtain substantially better results with the recommended 725 instrumentation-grade operational amplifier.

Figure 6 is a simpler circuit I've used with the Model C1 thermopile. This circuit gives an output of a few tenths of a volt when a hand is moved within 6 inches or so of the thermopile. Much greater output signals are given when the detector is illuminated by a small penlight or powered light-emitting diode.

Since the spectral response of this detector is almost flat, it's interesting to compare the output voltage given by various sources of ultraviolet, visible-light and infrared radiation. Try a candle flame, sunlight, a hot soldering iron, a xenon strobe light and various LEDs.

When using the Fig. 6 circuit, keep in

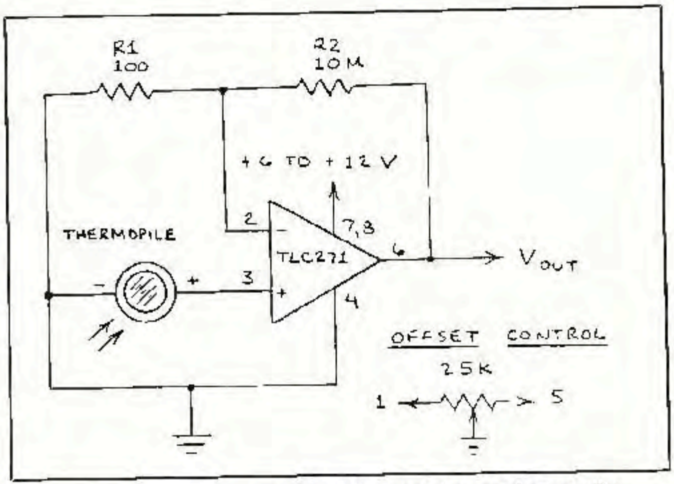


Fig. 6. A low-power amplifier for a miniature thermopile.

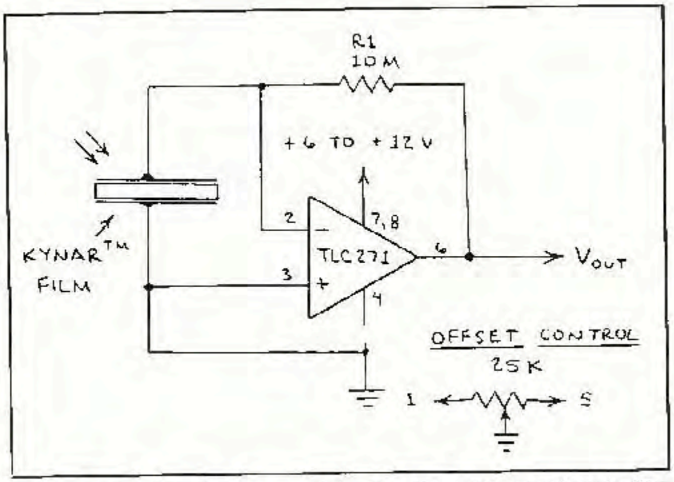


Fig. 7. A high-impedance amplifier for Kynar™ pyroelectric film.

mind that it is powered by a single-polarity supply. This means that the OFFSET CONTROL should be adjusted to give a small output from the amplifier when the thermopile isn't being irradiated. Otherwise, temperature changes that cause the output of the detector and the op amp to drift may force the output to zero even when the detector is receiving a signal. You'll have much better results observing the detector's response if you connect the output of the op amp to a multimeter with an analog meter movement than to one that has a digital numeric display.

The TLC271 op amp in the Fig. 6 circuit will also work with a dual-polarity power supply. For full details, see the Texas Instruments TLC271 data sheet.

Incidentally, the TLC721 is a CMOS op amp with a very high input impedance. Therefore, be sure to use safe MOS handling procedures when using it. You can use other kinds of CMOS op amps in this circuit as long as you revise the pin connections as necessary.

Experimenting With Pyroelectric Detectors

I described pyroelectric detectors in detail in the July 1987 "Electronics Notebook." That column included several tested circuits for lithium tantalate detectors made by Eltec Instruments, Inc. (P.O. Box 9610, Daytona Beach, FL 32020-9610). The circuits described in that column can also be used with ceramic pyroelectric detectors like those made by Amperex Electronic Corp. (George Washington Hwy., Smithfield, RI 02917).

I didn't cover plastic-film pyroelectric detectors in the July 1987 column. Kynar™ plastic piezoelectric film is the best-known pyroelectric plastic film. It's manufactured by Pennwalt Corp. (Kynar Piezo Film Dept., P.O. Box 799, Valley Forge, PA 19482). You can purchase a Kynar film kit from Edmund Scientific Co. (101 E. Gloucester Pike, Barrington, NJ 08007-1380).

You can easily make a large-area pyroelectric detector by connecting piece of metalized Kynar film to a high-input-impedance amplifier, such as shown in Fig. 7. Though I used a TLC721 CMOS op amp in this circuit, any high-input-impedance CMOS-type op amp should work.

For test purposes, connect the output of the amplifier to an analog-type multimeter that is set for a full-scale reading of 1 volt or less. As with the Fig. 6 circuit, be sure to adjust the OFFSET CONTROL to give a small output voltage at all times.

The Kynar film element I used measures approximately ¾ × 1½ inches. Therefore, its capacitance is considerably greater than that of miniature lithium tantalate and ceramic pyroelectric detectors. This greater capacitance slows down the detector's response time to as much as 1 second or so. If you place your hand near the detector, the output voltage will slowly increase by 20 or 30 millivolts, pause and then slowly begin to decline. The detector will also respond to the light from a flashlight or LED.

Going Further

Application circuits given here are only a hint of what can be done to process the signals from the various kinds of thermal detectors. For example, you can make a threshold alarm by connecting a comparator to the output of a detector amplifier. For monitoring the output of a detector in the dark, you can connect a LED bargraph display to the output of a detector amplifier. You can greatly increase the output of the thermal detectors by using them in conjunction with various kinds of lenses and reflectors.

Be sure to tune in next month to "Electronics Notebook," when I'll continue this discussion of detectors with a detailed look at phototubes, photodiodes, phototransistors and other photoelectric detectors. **ME**