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Infrared Thermal Detectors

Thermal sensing technology has come a long way since the first radiation thermometer was developed in the early 19th century. Review this survey of thermal sensing technologies—from thermopile sensors to pyroelectric detectors—before starting your next temperature-sensing design.

I remember being fascinated by infrared (IR) noncontact thermometers years ago when they first became popular in the consumer marketplace. The concept of measuring temperature at a distance almost seemed like magic at the time. I wanted to try one out for myself, but they were too expensive back then. Now that advances in sensor technology have brought costs down considerably, I was able to pick up a few different models to study (see Photo 1). This month I'll discuss various types of sensors used for measuring thermal radiation. I'll also describe how some products use them.

Any object with a temperature above absolute zero will radiate energy. The hotter an object, the more energy it emits and the shorter the wavelength of the energy. The total radiant energy is proportional to the fourth power of temperature. A radiometer is any device that measures this energy. If it's calibrated with a temperature scale, it's known as a radiation thermometer. If it's specifically designed to detect IR energy, it's commonly called an IR thermometer. The energy detected from an object also depends on its emissivity. That indicates how much of the energy is radiated from the object itself, rather than reflected off its surface from nearby sources. Many inexpensive IR thermometers assume a fixed emissivity of 0.95, which is reasonably accurate for most nonreflective materials.

THERMAL RADIATION

The first radiation thermometer was developed in 1828. It used the decidedly low-tech method of focusing thermal radiation onto the bulb of a thermometer using a concave mirror. In 1892, Henry Louis Le Chatelier created the first comparison-type optical pyrometer, which

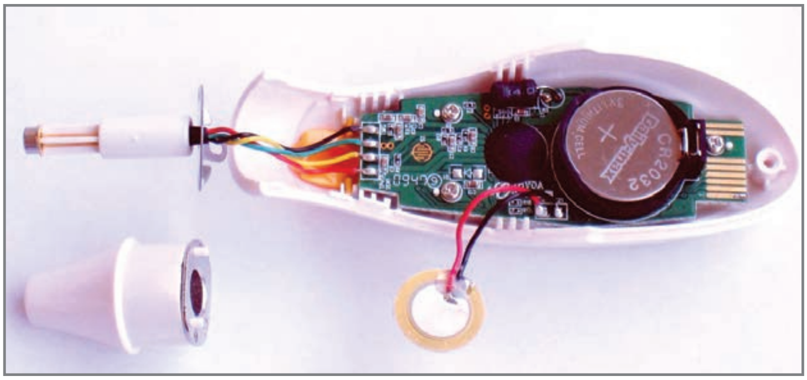


Photo 1—This is an inside view of an ear thermometer. The thermopile sensor fits snugly inside the cone-shaped tip, which you place in your ear to take your temperature. The dark blob next to the battery is the microcontroller. It's mounted chip-on-board, which is less expensive in high production volumes than using a packaged part. There's also a serial EEPROM on the back of the board to store calibration data and recent measurements.

Type	Sensor	Output
Thermal detector	Thermopile	Voltage
	Bolometer	Resistance
	Pyroelectric detector	Charge displacement
Quantum (photon) detector	Photovoltaic detector	Voltage
	Photoelectromagnetic detector	Voltage
	Photoconductive detector	Resistance

Table 1—Noncontact radiant energy sensors

was useful for measuring objects that were hot enough to glow. The user would adjust an iris diaphragm until the brightness of the object, seen through a viewing telescope, matched the flame of an oil lamp. The iris setting would then indicate the temperature. This technique was made more practical when an electric bulb replaced the oil lamp in the early 1900s. This instrument, known as a disappearing-filament optical pyrometer, still provides highly accurate temperature measurements for the steel and petrochemical industries.[1] Both of these devices required manual operation, a limitation that Charles Féry overcame in 1901 with the first radiation thermometer using a lens to focus thermal energy onto a thermocouple. The temperature could then be read directly from a galvanometer driven by the thermocouple.[2] By the 1950s this led to a more sensitive instrument using a photomultiplier tube as a detector, which evolved to the noncontact IR thermometers we have today.

Table 1 shows various commonly available sensors. Thermal detectors function by heating up as a result of absorbing thermal energy, which can take from milliseconds to seconds, depending on detector size. Quantum detectors measure incoming photons directly. This gives them greater speed, typically in the nanosecond-to-millisecond range. They are also more sensitive than thermal detectors, but operate over a narrower range of wavelengths that's dependent on the detector material. They often need external cooling to reduce noise when measuring temperatures at or below room temperature. We'll take a closer look at thermopile and pyroelectric detectors, since these are the most common noncontact IR sensors found in low-cost consumer-grade products.

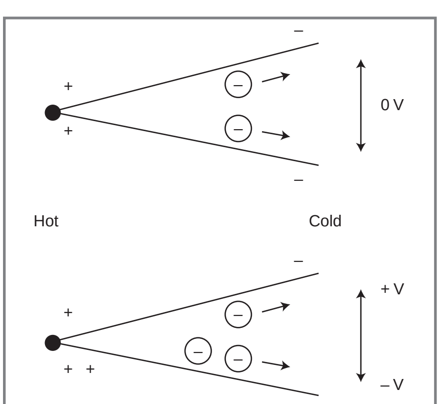


Figure 1—The thermoelectric effect in action. Heating two identical wires joined at one end has no net effect (top), but heating two dissimilar wires results in a measurable voltage (bottom).

THERMOPILE SENSORS

A thermopile consists of a number of series-connected thermocouples. To understand the operation of a thermocouple, we need to go back to 1821, when T. J. Seebeck discovered that a current flowed through two wires of dissimilar metals that were joined at both ends if one junction was at a different temperature than the other. This is known as the thermoelectric, or Seebeck, effect, and results from electrons diffusing from a hotter to a cooler section of wire. If you heat up part of a single wire, electrons will diffuse equally in both directions along the wire, causing a voltage gradient within the wire but no net voltage difference at its ends. But the diffusion rate varies for different materials. So, if you heat the junction of two dissimilar wires, the gradients will be different for each wire, and you'll see a voltage developed across the opposite ends of the wires. Figure 1 shows this phenomenon in action. The voltage is typically in the microvolt range for small temperature differences (below 100°C), so multiple thermocouples can be assembled into a thermopile to get a more manageable output signal. You can learn more about thermopile sensors in Brian Millier's article "Noncontact Infrared Thermometry" (*Circuit Cellar* 175, 2005).

Photo 1 shows the inside of an ear thermometer. It uses a thermopile sensor with a built-in reference thermistor. The thermopile provides a voltage related to the difference in temperatures between its hot and cold junctions, and the thermistor reports the temperature of the cold junction. A microcontroller combines these two values using the appropriate mathematical formulas to produce an accurate temperature reading of the hot junction. When you insert the thermometer properly into your ear, this reading will represent your internal body temperature. I wanted to see how easy it was to use the sensor's output directly, so I measured its output while varying the input temperature over the thermometer's stated operating range of 93.2°F to 109.4°F. I've read about certain Buddhist monks who can vary their body temperature while deep in meditation, but that wasn't very practical for my tests. Instead, I found I could aim the sensor at my desk lamp from a few inches away and cover the entire range by slightly varying the distance. The results of the experiment are shown in Figure 2. The curve has a slope of approximately 50 µV per °F.

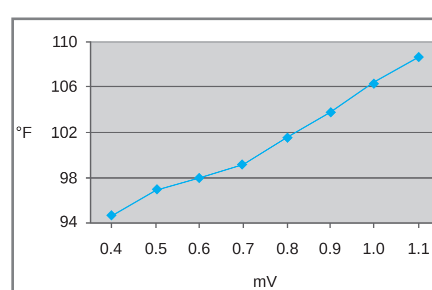
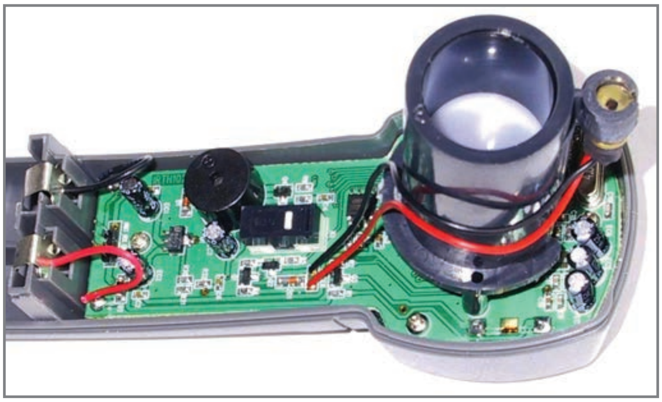


Figure 2—Sensor output of the ear thermometer. The nonlinearity in the curve isn't from the sensor. It came from slight variations in ambient temperature during the experiment as I moved the thermometer closer or farther away from the desk lamp.

Photo 2—A general-purpose noncontact thermometer. The Fresnel lens focuses incoming IR energy onto the sensor mounted underneath it. The copper-colored laser diode module (far right) points out the center of the area being measured.



The liquid crystal display (LCD) shows the temperature to a tenth of a degree, which would be a resolution of 5 µV. I find that rather impressive—there must be quite a bit of averaging being done to reduce noise. If you extrapolate the curve to the left, it would hit 0 mV at about 88°F. That's a reasonable value for ambient temperature, since the thermometer had been sitting under the desk lamp for a while by the time I started taking measurements.

You can also find thermopile sensors in general-purpose IR thermometers. Photo 2 shows one such device. The sensor is hidden underneath the plastic lens, but it's similar to the one used in the ear thermometer. This model has a laser pointer to locate the center of the sensing area. Thermopiles are also used in gas analyzers, where relative amounts of different gases can be measured by looking at the variations in IR absorption at different wavelengths.

PYROELECTRIC DETECTORS

A pyroelectric detector is a capacitive sensor that changes its polarization in response to a change in temperature. This results in a change in surface charge $\Delta Q = A \times p \times \Delta T$, where A is the sensor area, p is the pyroelectric coefficient of the material, and ΔT is the temperature change. It's inherently an AC-coupled device, so it needs some external process to cause the sensed temperature to change in order to produce any output. This makes it perfect for motion sensors, but it's also used for thermometers that use a mechanical shutter to produce a controlled change in input temperature.[3]

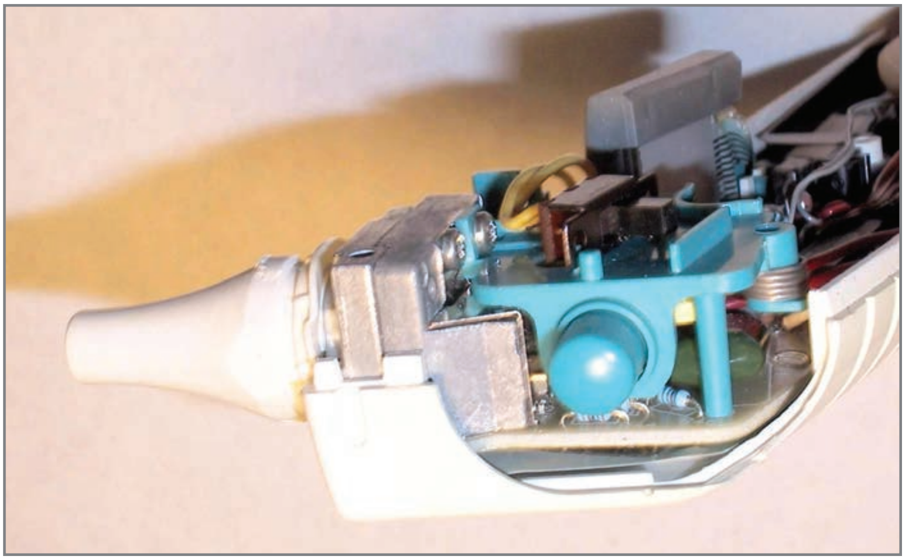


Photo 3—The sensing mechanism of an ear thermometer. It uses a pyroelectric sensor with a pushbutton-activated mechanical shutter. The metal block stabilizes the temperature of the entire mechanism.

Photo 3 shows the business end of an ear thermometer with a pyroelectric detector. This particular model is a few years old, but it serves as a useful example of detector operation. Normally, the detector is hidden behind a shutter that's mounted inside the metal block located to the left of the button. A thermistor mounted within the block tracks the temperature of the block and shutter. When you press the button, a spring-loaded mechanism snaps the shutter out from in front of the detector, giving it a clear view of whatever the probe is aimed at. The detector will output a signal that's a function of the difference in temperatures.

Figure 3 shows the thermometer's analog front end. It uses a dual-slope analog-to-digital converter (ADC) made up of a multiplexer IC and an op-amp integrator. You can follow the measurement process in Photo 4. Normally, the system repeatedly measures the temperature of the thermistor (SEL2:0 = 4,5) and the pyroelectric detector (SEL2:0 = 1,2). The cursors show when I pressed and released the Measure button. When pressed, the system immediately resets the integrator for 100 ms (SEL2:0 = 0) and then integrates the detector input for 200 ms (SEL2:0 = 1). Then it integrates a reference voltage until the comparator output goes high (SEL2:0 = 2). The input voltage is related to the integration times and multiplexer input resistors as follows:

$$V_{IN} = -V_{REF} \times \frac{R_{IN}}{R_{REF}} \times \frac{t_{REF}}{t_{IN}}$$

This formula applies to a steady input voltage, but you'll notice that the input isn't constant during the integration period. Rather, it is decaying with an RC time constant determined by the sensor capacitance and the sensor input op-amp stage's input resistance. Since this time constant is fixed, and the ADC's integration time always starts 100 ms after the shutter is opened and lasts for 200 ms, it's possible for the microcontroller to compute the value of the initial peak. It uses this value along with the thermistor value to compute the temperature.

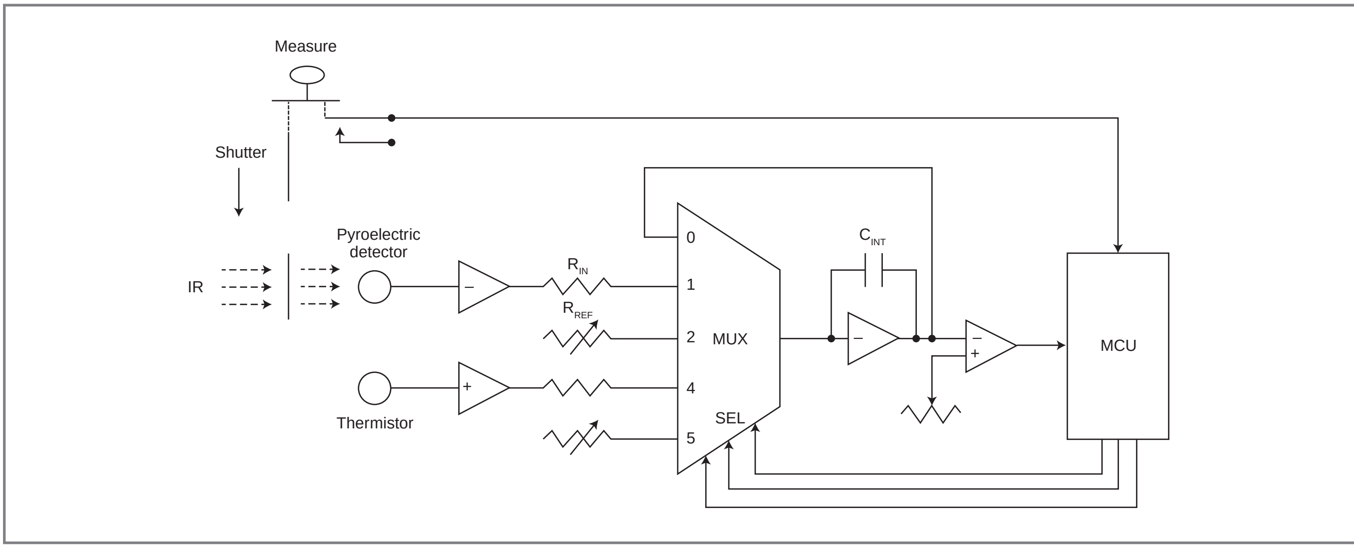


Figure 3—The pyroelectric ear thermometer's analog input circuitry and dual-slope ADC. Calibration is done using several adjustment pots.

Finally, let's look at a motion sensor, which is a more natural application for a pyroelectric detector since here the AC-coupled output is an advantage. The detector is slightly more complex, as it contains two pyroelectric elements connected in series back-to-back inside the package, separated by a fixed distance. Some detectors, including this one, also include an FET, which can be connected as a source follower to lower the detector's output impedance. In a motion sensor, the detector is mounted behind a Fresnel lens whose multiple segments alternately focus any incoming IR energy on one element then the other as a person walks by. Photo 5 shows this process as I waved my arm in front of a sensor. The SENSE signal normally sits at 1.04 V, and you can see it oscillating around this value as the lens alternately focuses the thermal energy from my arm onto each of

Photo 4—The ADC signals during a temperature measurement. You can see the multiplexer input select, comparator output, and integrating capacitor voltage. VSNS shows the pyroelectric sensor input signal shifting as I press and release the Measure button, indicated by the cursors.

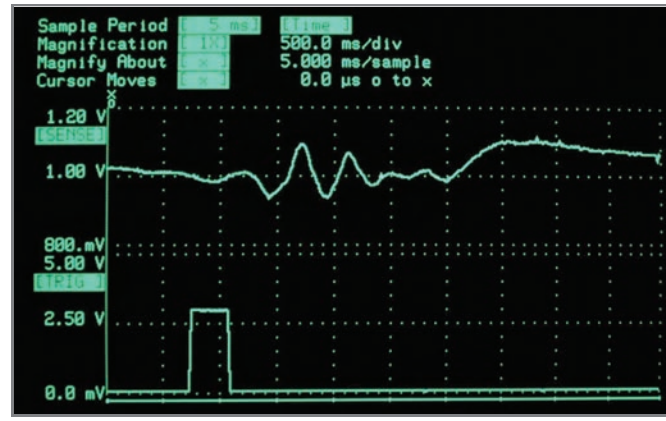


Photo 5—The motion sensor in action. SENSE is the pyroelectric detector output driving a 47-kΩ resistor and amplified by 100. TRIG shows when the output first exceeds the motion detection threshold.

the detector's two sensing elements. As the energy hits the first element, the detector's output goes positive momentarily. Then, as it leaves that element and hits the second one, the voltage across the first element goes negative while the second goes positive. The inverse series connection means these voltages will add, effectively doubling the output voltage. It's still not very large, only around 1 mV to produce the 100-mV peak shown in the photo.

COOLING DOWN

I hope I have helped take some of the mystery out of thermal IR sensors and their everyday applications. I'm ready to do more exploring now that I have a handful of sensors to work with. Maybe you are now inspired to take a closer look at some firsthand.

Richard Wotiz has been taking products apart ever since he was old enough to pick up a soldering iron. He's been helping others put them back together since 1991, when he started his design consulting business. Richard specializes in hardware and software for consumer products and children's toys. He can be reached at rw601@spiraltap.com.

REFERENCES

[1] D. DeWitt and G. Nutter, "Theory and Practice of Radiation Thermometry," Wiley-Interscience, 1988.

[2] C. Féry, "Thermoelektrisches Pyrometer," German Patent 135064, 1901.

[3] J. Fraden, "Infrared Electronic Thermometer and Method for Measuring Temperature," U.S. Patent 4797840, 1989.