Thermistors in Homebrew Projects

Thermistors are inexpensive, readily available components. Better yet, they can greatly enhance the performance of your projects. Learn how to put them to work for you.

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Thermistors are interesting compnents that Amateurs can use to enhance their projects. Variations in circuit temperature that affect gain, distortion and control functions such as receiver AGC or transmitter ALC can be compensated. Dangers of self-destruction of overheated power transistors can be greatly reduced. Oscillator drift can be greatly reduced. This article discusses thermistor properties and shows three examples of how they can improve project performance. We will see first that some easy mathematics improves the understanding.

Mathematics of Thermistors

A thermistor is a small bit of intrinsic (undoped) semiconductor material between two wire leads. As temperature increases, the number of liberated hole-electron pairs increases exponentially, causing the resistance to decrease exponentially. This exponential nature is seen in the resistance equation:

$$R(T) = R(T0) \bullet e^{-\beta\left(\frac{1}{T0}-\frac{1}{T}\right)} \qquad \text{(Eq 1)}$$

where T is some temperature in Kelvins and $T0$ is a reference temperature, usually 298 K (25°C), at which the manufacturer specifies $R(T0)$. The constant β is experimentally determined by measuring resistance at various temperatures and finding the value of β that best agrees with the measurements. A simple way to get an approximate value of β (this is usually all we need in ham-gear design) is to make two measurements, at room temperature, say $T = 25$ °C (298 K) and $T0 \approx 100$°C (373 K) in boiling water. Suppose the resistances are 10 kΩ and 938 Ω. Eq 1 is solved for β:

$$\beta = \frac{\ln\left[\frac{R(T)}{R(T0)}\right]}{\frac{1}{T}-\frac{1}{T0}} = \frac{\ln\left(\frac{938}{10000}\right)}{\frac{1}{373}-\frac{1}{298}} \approx 3507 \qquad \text{(Eq 2)}$$

Usually, the exact value of temperature is not as important as the ability to maintain that temperature. A better estimate of β, if needed, can by achieved by a linear regression method using the program *THERMIST.BAS*, downloadable from the *ARRL QEX* Web site.[1] This program takes the logarithm of both sides of Eq 1, which provides a linear relationship between $\log(R(T))$

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[1] You can download this package from the ARRL Web http://www.arrl.org/qexfiles/. Look for THERMIST.ZIP.

and (1/*T0* – 1/*T*). Five equally spaced data points are input to get the slope of the line, which is *β*.

The following examples illustrate a few of the main ideas of thermistor-circuit design that can be employed in a number of similar situations.

MOSFET Power-Transistor Protector

It is common practice to compensate the temperature sensitivity of power transistors. In bipolar (BJT) transistors, thermal runaway occurs because the dc current gain increases as the transistor gets hotter. The runaway condition is less likely to occur in MOSFET transistors, but with excessive drain dissipation or inadequate cooling the junction temperature will increase until its maximum allowable value is exceeded. A common procedure is to mount a diode or thermistor on the heat sink close to the transistors, so that the bias adjustment tracks the flange temperature. References 1 and 2 give detailed discussions of this.

A special problem occurs when a sudden large increase in transistor dissipation occurs. The flange temperature changes rather slowly because of the thermal capacitance (heat storage) of the heat sink. However, the junction temperature rises much more rapidly and can rise above the maximum limit before the correction circuit has a chance to function. If a thermistor is attached to the ceramic case with a small drop of epoxy as shown in Fig 1 it will respond much more rapidly (shorter time constant) and *may* (not guaranteed) save the transistor. The circuit (Reference 3) of Fig 2 detects a case temperature of about 93°C and completely turns off the FETs until the case temperature drops about 0.3°C, at which time the FETs are turned on again. A red LED on the front panel warns of an over-temperature condition that requires attention.

In Fig 2, a 4.7 V Zener (D1), *R1* (metal film) and *R*th (thermistor) are a voltage divider with an output of 0.6 V.

If this voltage decreases slightly (because the resistance of *R*th decreases slightly) Q1 starts to come out of saturation, Q2 quickly goes into saturation and the gate voltage of the FET goes to a low value, turning it off. At the same time, the 20-mA LED (RS 276-307) lights. The voltage divider equation is:

$$0.6 = 4.7 \bullet \left(\frac{R\text{th}}{R1 + R\text{th}} \right) \qquad \text{(Eq 3)}$$

If we solve this for *R1*, we get:

$$R1 = 6.831 \bullet R\text{th} \qquad \text{(Eq 4)}$$

If the value of *R*th is known at some temperature, then *R1* is the value that activates the circuit at that temperature. An interesting feature is that the voltage across the thermistor never exceeds about 0.6 V, and this greatly reduces the self-heating of the thermistor, which could otherwise cause a substantial error in the circuit behavior. The temperature variations of Q1 and D1 are small sources of error, so this simple circuit should be placed in a cool location, not directly on the heat sink.

The RadioShack precision thermistor (RS 271-110) is rated at 10 kΩ ±1% at 25 °C. It comes with a calibration chart from –50°C to +110°C that can be used to get an approximate resistance at some temperature. We are most interested in FET case temperatures in the range of 70°C to 100°C. It is assumed that very close temperature knowledge is not needed, but in order to be sure that the thermistor is okay, I measured its resistance at 20°C (68°F) and in boiling water (≈100°C). The circuit of

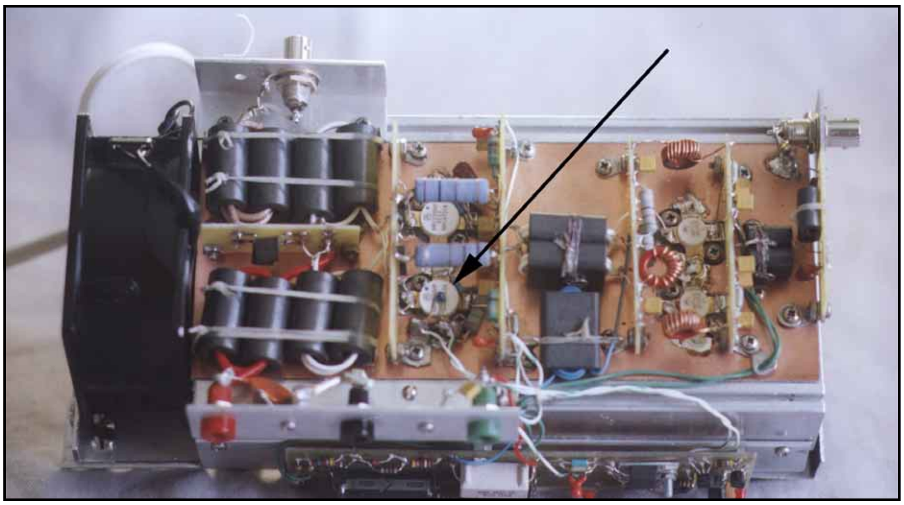

Fig 1—The thermistor attached to power MOSFET with a drop of epoxy.

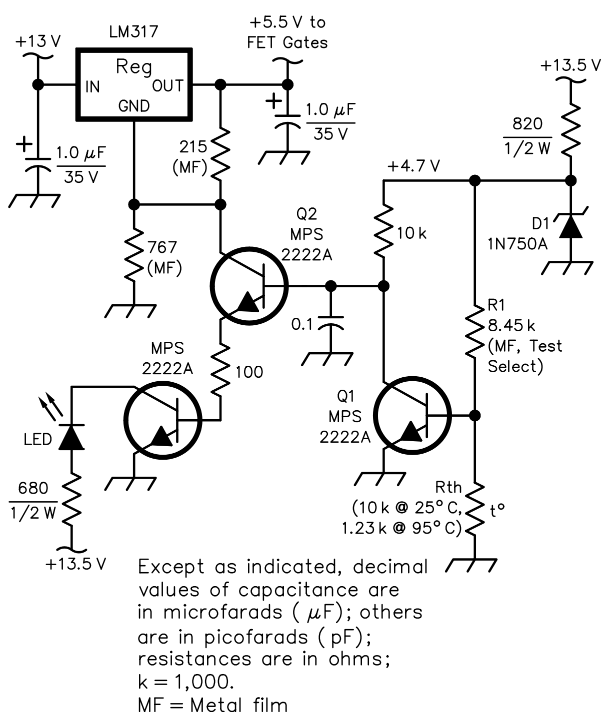

Fig 2—Schematic of a MOSFET temperature-protection circuit.

Fig 2 is intended for 50°C or greater when the 10-kΩ thermistor is used. At lower temperatures, the circuit of Fig 3 would be better.

The following procedure was used to get the desired temperature control:

1. The MRF150 MOSFET has a maximum allowed junction temperature of 200°C. The thermal resistance θ_{JC} from junction to case is 0.6°C/W.
2. The maximum expected dissipation of the FET in normal operation is 110 W.
3. I selected a case temperature of 93°C. This makes the junction temperature 93 + (0.6) (110) = 159°C, which is a safe 41°C below max.

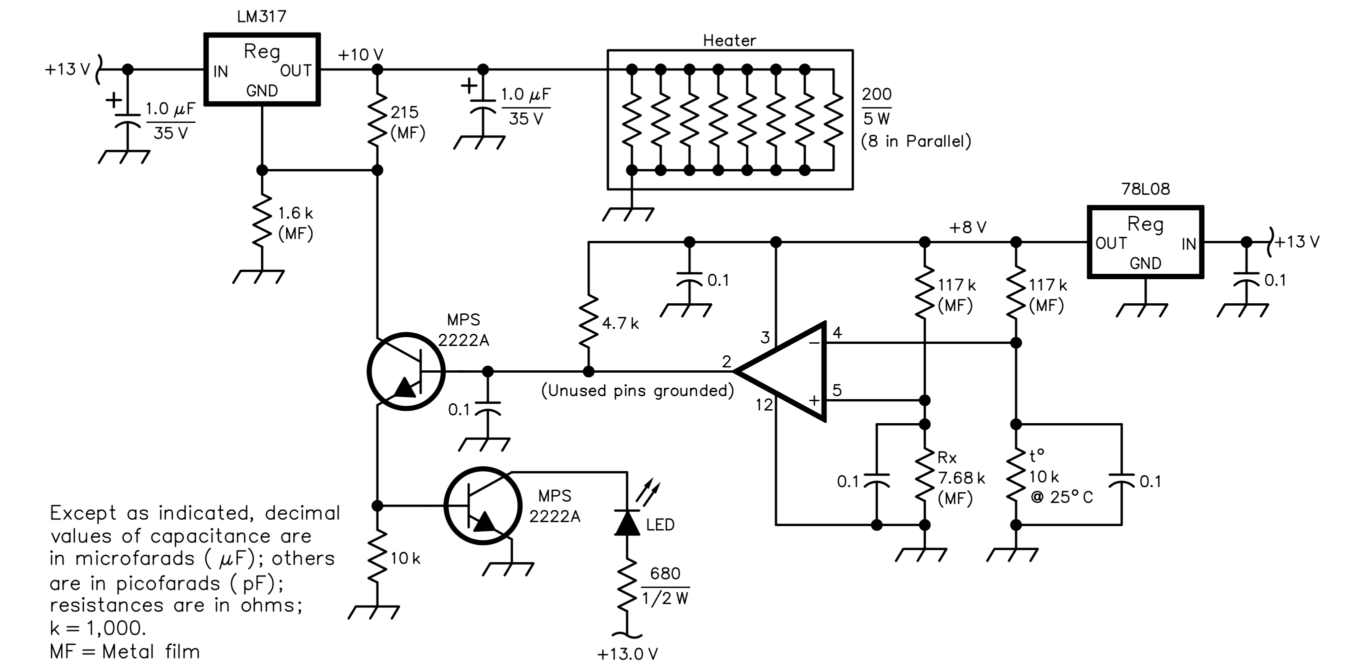

Fig 3—A VFO temperature-controller schematic. The eight 200-Ω resistors labeled "Heater" serve to warm the VFO enclosure

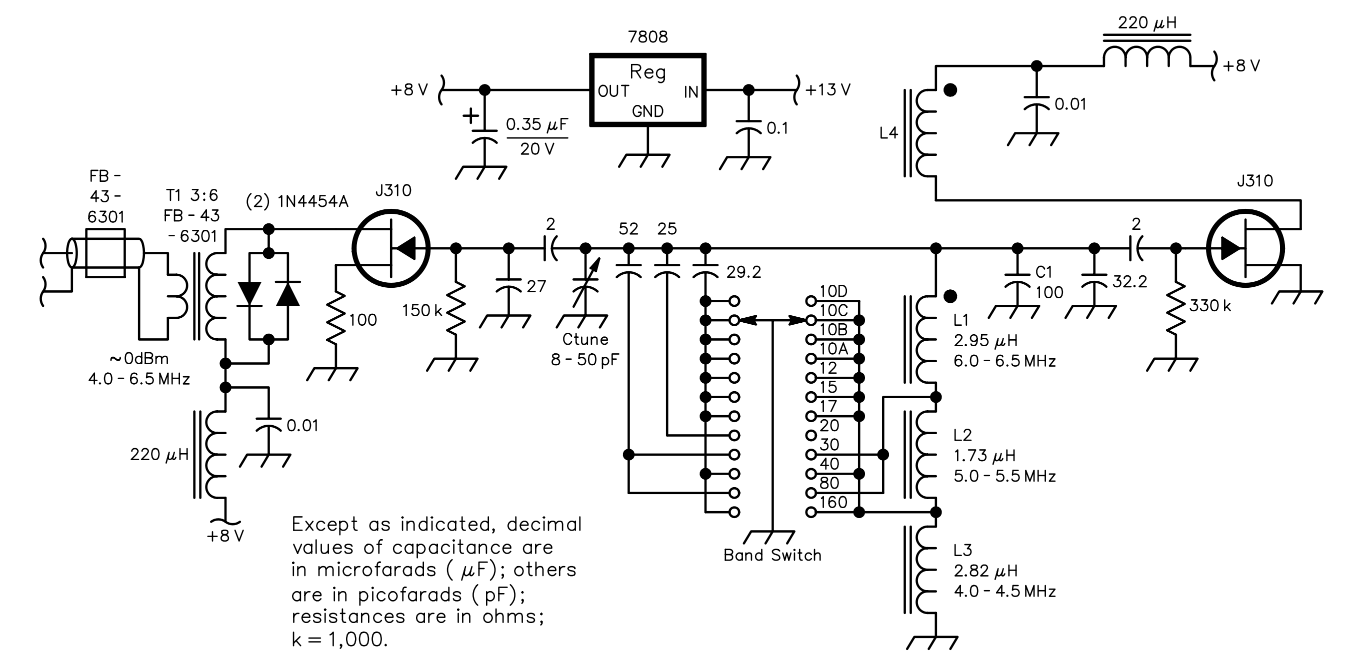

Fig 4—Schematic of a three-band VFO.
L1—22 t #24 AWG, wide spaced on a T68-7 core
L2—17 t #24 AWG, wide spaced on a T68-7 core
L3—22 t #24 AWG, wide spaced on a T68-7 core
L4—2 t #24 AWG link, close wound on L1 core
SW1—Electroswitch D4C0312N
Ctune—Hammarlund RMC-50-S

4. The FET has a rating of 300 W maximum dissipation at a case temperature of 25°C, derated at 1.71 W/°C. At 93°C case temperature, the maximum allowed dissipation is 300 – 1.71 (93 – 25) = 184 W. The safety margin at that temperature is 184 – 110 = 74 W.
5. A very simple way to determine the correct value of *R1* is to put the thermistor in 93°C water (let it stabilize) and adjust *R1* so that the circuit toggles. I found that 8450 Ω was the nearest standard value for a metal-film resistor. At 93°C, the measured value of the thermistor was about 1230 Ω.

Measurements of the circuit sensitivity determine the temperature values at which the circuit toggles on and off. I replaced the thermistor with a resistor decade box and measured resistances of 1224 Ω and 1234 Ω. Solve Eq 1 for the *T* that corresponds to each value of *R*:

$$T = \frac{\beta}{\ln\left(\frac{R}{R0}\right) + \frac{\beta}{T0}} \qquad \text{(Eq 5)}$$

which is easy to perform with a handheld calculator or math program such as *MathCAD*. Using the two values of *R*, I found a temperature range of about 0.3°C.

A Temperature Controlled VFO

The circuit of Fig 3 is used to control the temperature of the three-band VFO shown in Fig 4, inside a thermally insulated enclosure. The Wheatstone bridge circuit with an LM339 comparator as a null detector is more sensitive and less temperature dependent than Fig 2. The ’339 works quite well at a level of 0.5 V at each of its two inputs. This circuit is preferable at lower temperatures, such as 30 to 35°C, where the thermistor resistance is in the 8 k to 7 kΩ range.

I use eight 200 Ω, 5 W metal-oxide resistors at the output of the LM317. The total heat applied is 4 W to maintain 33°C, and the resistors are placed so that their heat is distributed uniformly: Half are placed near the bottom and half near the top. The thermistor is mounted in the center of the box (see Fig 5), close to the tuned circuit and in physical contact with the oscillator ground-plane surface, using a small drop of epoxy.

The enclosure is homemade from sheet aluminum and angle stock. It is large enough that it has almost no effect on frequency. The outside is lined with 1/4-inch plexiglass and the inside surfaces are lined with 1/4-inch Styrofoam sheets. The tuning and bandswitch shafts are thermally insulated from the outside world, using plastic shaft couplers. Plexiglass blocks attach the box to the front panel. Electrical grounding is via an RF choke (for dc) and several 0.01 µF capacitors (for RF).

The temperature at the thermistor location is maintained within 0.1°C, as determined by thermistor resistance measurements. Using the method of the previous example to get the temperature range and knowing the frequency drift versus temperature coefficient of the VFO in parts per million (PPM), the frequency change can be found as follows:

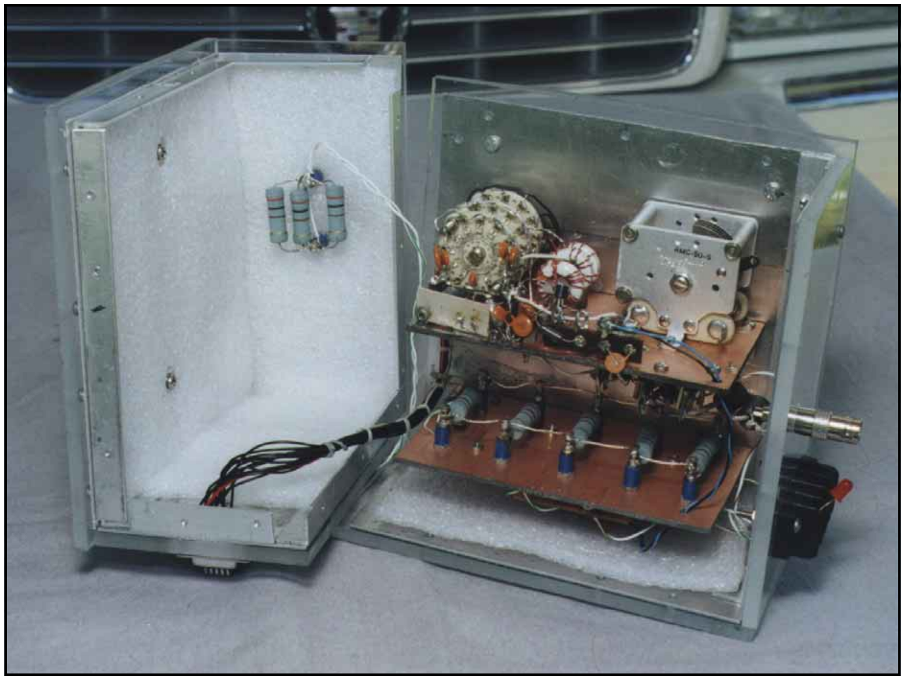

Fig 5—The three-band VFO with temperature control. Five of the eight 5-W resistors are mounted on a circuit board to the right of and slightly below center. The other three 5-W resistors are wired together slightly to the left and above center. The thermistor is not visible in this photo.

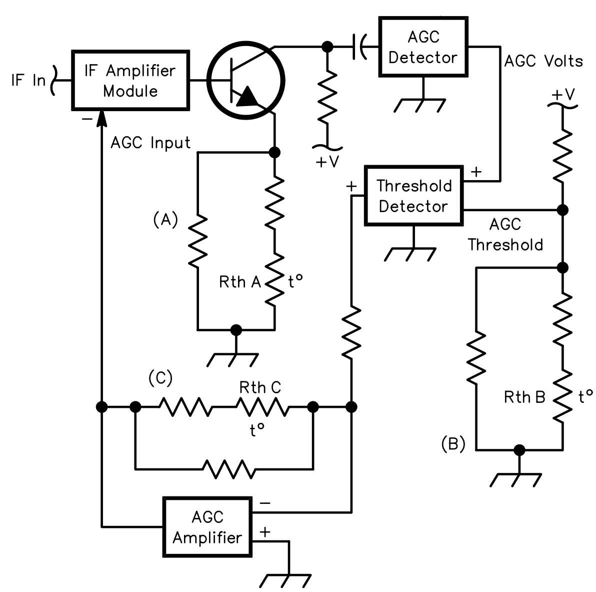

Fig 6—Temperature compensation of IF-amplifier and AGC circuitry: (A) IF amplifier, (B) AGC threshold, (C) AGC gain. Each compensation circuit uses two resistors and a thermistor (RthA, RthB or RthC).

$$\Delta F = F_{VFO} \bullet PPM \bullet \Delta T \qquad \text{(Eq 6)}$$

Plugging in some numbers encountered for a 4.0 to 6.5 MHz VFO with PPM = –500/°C and Delta T = 0.1, before temperature compensation,

$$\Delta F = 6{,}000{,}000 \bullet \frac{-500}{1{,}000{,}000} \bullet 0.1 = -300 \text{ Hz} \qquad \text{(Eq 7)}$$

which indicates that some improvement is needed, in particular the temperature coefficient. If the enclosure is massive or well insulated, the rate of temperature change can be slowed down. When a small temperature range of 0.1°C was maintained, the VFO temperature coefficient was improved by a factor of about seven with a negative-temperature-coefficient capacitor, C1. Inexpensive polystyrene capacitors, for example Mallory type SX, have a well-controlled negative (–120 PPM/°C) temperature coefficient that is intended to offset the positive temperature coefficient of inductors. (Caution: To prevent damage, use pliers on the leads as a heat sink when soldering.) No other temperature compensation was needed (probably fortuitously).

Temperature-compensating capacitors are available from Surplus Sales of Nebraska (**www.surplussales.com**). Other suitable fixed ceramic capacitors are Vishay 561 series, type 10TC NP0, which I have found are excellent. No variable trimmer caps are needed because each VFO band has a 25 kHz margin at each end and a calibrated analog dial is not used. The two-turn feedback winding in the J310 drain satisfies all three coils. The three inductors use Carbonyl-TH, T68-7 cores (white paint), which are claimed by Amidon to be the most temperature-stable mixture at normal room temperatures.

The oscillator finally turned out to be very slightly overcompensated. Over the 0.1°C range, the frequency varies ±20 Hz or less, with a period of about five minutes. Superimposed is a very slow drift of average frequency that is due to settling of component values, including possibly that of the RadioShack thermistor. These gradual changes became negligible after a few days of continuous operation.

One problem that is virtually eliminated by maintaining a constant temperature is the "retrace" effect on cores and capacitors. Because of "retrace," components subject to a substantial temperature transient of some kind may take several hours to recover their previous L and C values. The thermistor may also show a retrace effect.

Reference 4 shows ways to perform the temperature compensation operation and gives further references. An especially good method is to toggle the value of *Rx* (Fig 3) slightly so that a variation of ±0.5°C is created inside the VFO enclosure, and then do the temperature compensation. Because of the small average power dissipation in the VFO plus controller, it is economical to let the VFO run continuously so that initial warm-up drift (measured less than 1 kHz) and retrace are avoided.

If the VFO is mixed with crystal frequencies and then bandpass filtered (the "mix-master" approach) the final local oscillator (LO) can be quite stable and very clean spectrally. This is especially so if the crystals (±20 PPM/°C *maximum*) are temperature compensated, temperature controlled or even phase-locked to a reference (see Reference 5). An LO frequency counter (see Reference 6) offset by the IF is a very simple and excellent way to read the actual RF signal frequency to within ±50 Hz, if the reference crystal is of high quality and perodically adjusted to WWV. The frequency stability is quite adequate for HF SSB/CW, which are the primary applications for this equipment. Listening tests confirm that in SSB speech, slow frequency changes of ±50 Hz are hardly noticed. The reason for the three bands of the VFO (4.0-4.5, 5.0-5.5, 6.0-6.5 MHz) is to minimize spurious mixer products due to harmonic intermodulation that can slip through the LO bandpass filters.

Gain and AGC control

Thermistors are used to stabilize, or to vary in a controlled manner, the gain of an amplifier or an on-off threshold. Fig 6 sketches three examples. Fig 6A is the final IF amplifier stage that is part of an IF amplifier module. The thermistor compensates the gain variation of the module. Figs 6B and 6C are part of the receiver AGC circuit. The thermistors compensate for variations in AGC slope (dB/V) and vary the AGC threshold.

In all cases, use a resistor decade box to determine the resistance-temperature correlation and plot an RT curve. Then look for a resistor-thermistor circuit that seems reasonable. A *MathCAD* or *Excel* worksheet is then an elegant way to get the component values experimentally by comparing the thermistor-circuit temperature curve with the desired RT curve. Usually, a close approximation is good enough, and perfection is not justified. (Catalogs offer a wide assortment of thermistors for these projects.) The method suggested in Fig 6, one thermistor and two resistors, is a simple combination that gives a good approximation to the desired RT curve. In many cases, one of the resistors can be deleted. Reference 7 shows other useful and interesting thermistor applications.

References

1. N. Dye and H. Granberg, *Radio Frequency Transistors*, Chapter 4, (Boston: Butterworth-Heinemann, 1993).
2. H. Granberg, "Wideband RF Power Amplifier," *RF Design*, Feb 1988. Also *Motorola RF Applications Report* AR313 (1993), p 424.
3. W. Sabin, W0IYH, "A 100-W MOSFET HF Amplifier," *QEX* Nov/Dec 1999. See also "Letters to the Editor," *QEX*, Mar/Apr 2000, pp 60-61.
4. *ARRL Handbook* (Newington: ARRL) 1995 to 2000 editions, Chapter 14. Order No. 1832, $32. ARRL publications are available from your local ARRL dealer or directly from the ARRL. Check out the full ARRL publications line at **http://www.arrl.org/catalog/**.
5. See Chapter 17 of the *ARRL Handbook* for a description of the Ten-Tec Omni VI Plus transceiver.
6. Radio Adventures Co, RR4 Box 240, Summit Dr, Franklin, PA 16323; tel 814-437-5355, fax 814-437-5432; **information@radioadv.com**; **http://www.radioadv.com**. Model BK-172. For a description, see the 1999/2000 *ARRL Handbook,* Chapter 26.
7. P. Horowitz and W. Hill, *Art of Electronics*, Second Edition (New York: Cambridge University Press, 1989).