A quartz crystal oscillator in a temperature stabilised enclosure to be used as a reference for a counter or narrow-band mode receiver or transmitter at UHF/SHF

The need for this reference arose in my shack when I was using a 1 GHz counter to measure frequencies in the 450 MHz region and finding errors of the order of 3 kHz. This is not that much, as a percentage but even for FM, it is a significant part of the bandwidth of a narrow-band FM signal. As the frequency is increased, the requirements on the stability and accuracy of a reference become more demanding. The original reference in the counter was a simple microprocessor crystal in a CMOS type oscillator. It was calibrated some years ago but had obviously drifted off. So the idea for this more stable reference was born. The ultimate aim is to lock its frequency to the horizontal sync pulses of a TV signal along the lines of Ref 1. The TV networks use accurate standards to generate their sync pulses. The ABC derives its reference from Global Positioning System signals.

Design
There are two main causes of drift in the frequency of quartz crystal oscillators, namely temperature changes and aging of the crystal itself. To make a high stability oscillator therefore requires that both these causes of drift be compensated for. Putting the crystal and often, its associated oscillator components in a temperature-stabilised oven has long been a means of reducing or removing the effects of temperature. There is not much the average amateur can do about aging of the crystal other than obtaining the best quality crystal.
that can be afforded given the requirements of the application.

More recent reference oscillator designs use a temperature sensor such as a thermistor and adjust the frequency of the oscillator based on the sensor output. This may be done by directly coupling the thermistor to a varicap or if more accuracy is required a microprocessor may be used. The temperature reading is brought into the micro via an A-D converter and a lookup table used to determine the output voltage required on a varicap to correct the frequency. The digital representation of the output voltage is then applied to a D-A converter and then to the varicap. This latter method can be made very accurate as the table of values in the micro can be tailored to the particular crystal.

These two methods of compensating for temperature changes generally result in very low power consumption for the oscillator and its compensation and therefore are well suited to modern battery operated equipment. However, they are not easy for an amateur to reproduce, building a one off reference. Therefore I have chosen to take the old “tried and true” method of putting the whole oscillator and buffer in a temperature stabilised enclosure with good insulation to minimise the power consumption of the heater once the internal temperature has stabilised.

I tackled the design and building of the oven controller first as I reasoned that if I couldn’t get that right, there was no point continuing. As it turned out, the controller works very well to the point that temperature variations at the internal temperature has stabilised.

The components and the thermistor. The heater transistor makes stabilising of the temperature constant within as close limits as possible. Close thermal coupling between the heater and the crystal as tight as possible. The heater is a PNP power transistor in a large TO-218 tab package screwed to a copper heat spreader. The thermistor is soldered to a lug under the transistor fixing screw, making good thermal contact. The crystal is clamped to the heat spreader alongside the heater transistor. The layout is illustrated in the photographs. The heat spreader is a 60 mm length of 25 by 3 mm copper bus bar.

**Circuit Description - Oven Controller**

Refer to Fig.1, the oven controller circuit. This circuit is a feedback control system in which the temperature is sensed by a thermistor and any error between it and a reference is amplified and used to control the heater. IC2 is a precision voltage reference of 6.9 volts, providing a precise supply for the resistance bridge R2, R3, R4 and the thermistor, TH1. The latter has a resistance of about 220 k at 25 deg and 68 k at 60 deg. Any imbalance in the bridge is applied to the op amp IC1 which amplifies it and passes a correction voltage to the heater driver transistor, TR1. If the temperature is too low, TH1 is higher than R2 and the plus input to the opamp, pin 3, goes positive causing the output to rise. This results in TR1 drawing more current, which flows out of the base of TR3. TR3’s emitter current rises until the voltage across R10 causes TR2 to turn on. This shunts current away from TR3 base, limiting the emitter current to about 300 mA. This configuration of a current limiting transistor (TR2) in the base circuit of another to protect the latter from excess current is a very useful one, which can be quite widely applied. In fact it is commonly used in the output circuits of IC’s, both digital and analogue.

TR3 dissipates about 3.5 watts when hard on and heats up the oscillator components and the thermistor. The thermistor voltage falls lowering the correction voltage into the opamp which reduces the current in TR1 and therefore TR3. The diode D1 ensures that when the opamp output is at its lower limit which is about one volt, TR1 remains off since two diode voltage drops (1.3 volts) are required to turn TR1 on.

The components C1 and R7 are for frequency compensation of the control loop. Without them the loop is unstable with hum and noise picked up on the opamp input causing large amplitude oscillations at the opamp output. In addition, the loop tends to “hunt” with the heater going from hard on to hard off. The resulting temperature fluctuations cause the oscillator frequency to fluctuate as well, after all, the idea of the oven controller is to keep the temperature constant within as close limits as possible. Close thermal coupling between the thermistor and the heater transistor makes stabilising of the control loop easier. I found that placing the thermistor on the heat spreader 15 mm away from the transistor fixing screw resulted in a thermal delay which was difficult to compensate for. The drill hole where the thermistor was placed initially can be seen in photo 2. As it is, the compensation is close to ideal with only a little overshoot of temperature during warm-up.

**10 MHz Oscillator**

The oscillator circuit, Fig 2, shows the details of the Colpitts crystal oscillator and buffer amplifier. This is a version of the Colpitts oscillator using a darlington
Figure 2. 10MHz Reference Oscillator
connection of two transistors, TR1 and TR2. I have used it in the past and found it to be more reliable than the single transistor version. The crystal is on its parallel resonance frequency and the frequency can be adjusted by changing the capacitance seen by the crystal. Both electrical and mechanical adjustments are provided for by a varicap and a good quality air dielectric trimmer. With the trimpot R15 set at about the centre of its range, varying the frequency tuning voltage from zero to 5 volts causes the oscillator frequency to increase by about 3 Hz.

The high gain of the darlington connected transistors enables larger values of feedback capacitors C7 and C8 to be used. This provides improved isolation of the crystal from variations in transistor parameters. Transistor parameter variation due to temperature is minimised by clamping the two oscillator transistors to the heat spreader alongside the crystal. Likewise the varicap is placed in thermal contact with the heat spreader. I put thermal grease on all the mating surfaces to help keep the temperature more uniform.

The oscillator output is lightly
coupled to a dual gate mosfet TR3, through capacitor C9. TR3 has very low feedback capacitance (of the order of 0.02 pF) and therefore there is very little effect on the oscillator from influences at the buffer output. The drain circuit of TR3 contains an autotransformer, T1 with the centre tap coupling signal to the base of the output emitter follower, TR4. A resistor, R14 is included in series with the emitter of the output transistor to make the output impedance close to 50 ohms. The output power in the prototype was 8 dBm or about 1.6-volt p-p into 50 ohms.

Construction

The two sections of the reference are constructed on the one circuit board separated by the copper heat spreader. Photo 2 and the layout diagram Fig. 3 show the arrangement of components. The heat spreader is held onto the circuit board with two screws and spacers to separate it from the circuit board, though in retrospect, this is probably not necessary or even desirable. There is a clamp over TR3, the crystal, TR1 and TR2 but it has been removed for the photograph. Springy copper leaves can be seen soldered to the underside of the clamp to press the crystal and the two transistors onto the heat spreader.

The thermistor is soldered to a solder lug under the heater transistor mounting screw. The thermistor originally comes with two wire leads and to solder it directly to a solder lug, scrape the paint off one side of the thermistor, unsolder the wire and solder that side of the thermistor to the previously tinned solder lug. Place the thermistor as close as possible to the mounting hole in the lug, leaving enough space for the screw head. An insulating sleeve should be placed over the remaining wire, which is run to a hole in the circuit board. The oscillator transistors TR1 and 2 are in plastic TO-92 packages and are mounted flat side down on the heat spreader. The varicap is placed in a dob of heatsink compound adjacent to the transistors. A small ferrite toroid is used for the core of autotransformer, T1 with a bifilar winding of 7 turns of 0.3 mm (about 30 SWG) enamelled copper wire. Toroid types FT23-43 or FT-37-43 would be fine.

The circuit board is a piece of single sided copper laminate with the components mounted on the copper side which acts as a ground plane for the whole circuit. Most of the component leads go through holes in the board and the non-grounded ones have the holes slightly countersunk to prevent shorting to ground. Inter-connections are made underneath the board using mostly just the component leads. This is a method that I have developed after less than satisfactory results making medium density PCBs at home. I lay out the board using a computer package (Protel) in the normal way as if I were making a PCB but instead of etching the board, I use the top overlay diagram as a template to drill the holes.

First thoroughly clean the copper side of the board with steel wool and water then tape the layout diagram over the copper side. Use a punch to make pop marks through the paper where the holes are to go. Next remove the paper and drill all the holes with the smallest size of drill. I find 0.8 mm is a good one for most components. The larger holes can be bored out to the correct size later. Now we have to countersink those holes where leads pass through the board without connecting to the ground plane. I find it much easier to make the solder joint to ground if the hole is not countersunk, so mark with a felt tip pen those holes where a ground connection is to be made. Most inks in these pens can be soldered through so don’t worry about the ink preventing a good solder connection. Try to mark all the earth holes so as not to countersink them but don’t worry if you miss one or two as it is still possible to solder the lead to the ground plane around a countersunk hole. It just takes a little more solder.

All the unmarked holes can now be countersunk. Do this very carefully with a small drill bit. 2.0 mm is about right. Only a slight countersink is required, just enough to remove the burr around the hole. A 1.5 mm countersink diameter is plenty. The board is now ready for loading the components except for one thing. It is a good idea at this stage to spray the copper side with PCB lacquer to keep it shiny looking. If you are using IC sockets it is useful to cut away a bit of the plastic housing of the socket above any pins which are grounded. Doing so makes it much easier to solder the pin directly to the ground plane once the socket is inserted in the board. This is most applicable to the corner earth pin of logic and opamp IC’s but can be done with all earthed pins. Terminals for power input and signal output are made to pins soldered to isolated pads in the ground plane. These pads can be cut with a PCB counterbore available from Farnell Electronics (Cat. No.146-413) They aren’t cheap at $22 or so but do a nice job of cutting round pads in the ground plane. It isn’t necessary to cut these isolated pads, though. The 0.8 mm hole can be drilled out to the size appropriate for the pin that you have and the pin will be retained in the countersunk hole by the solder joint under the board.

Components can now be placed in the
board a few at a time and the underside connections made. Solder the connections as you go rather than putting many components in then turning the board over. This will prevent the components falling out when you turn the board over to make the solder joints. Inevitably some connections will be required which cannot be made with the existing component leads. To make the shorter connections, I have retained a large number of offcuts of component leads in a flat tin so that when a short connection is required I use one of those. For the longer links I use single strand kynar insulated wire, the type used for wire wrapping but any ordinary hookup wire will do.

This may all sound messy and time consuming compared with simply dropping the components into a PCB and soldering them in place, but I have found it preferable to generating a PCB layout, transferring it to coated board or using a toner transfer process then etching the board in the XYL’s laundry often with not entirely satisfactory results.

An etching pattern is provided for the bottom side of the board for those who wish to etch their own. Double sided laminate should be used and the top side protected from etching by covering with adhesive tape or adhesive “Contact” film.

The board in the original is mounted in a box fabricated from 1.5 mm zinc annealed steel. The corners were welded at a local workshop for $10. Two coats of self priming spray paint gave a nice finish to the box. The lid is secured with two screws in opposite corners of the lid going into threaded spacers screwed to the bottom of the box. Insulation was cut from a sheet of 20 mm thick polystyrene board with pieces on all 6 sides of the box. A diecast box would serve very well if you don’t want to roll your own and even a plastic “zippy box” would do although a metal box is preferred for RF screening.

Testing

I built and tested the oven controller section first. When you first power it on having checked your wiring, monitor the supply current. It should start out at between 300 and 350 mA falling to a level dependant on how well the board is insulated. Initially, it probably isn’t insulated at all, so the current will vary depending on draughts blowing across the board. Check that the reference voltage is correct, 6.9 volts with the LM329 device shown on the circuit. Look at the voltage on the output of the opamp. It should be free from large variations or oscillation. If you have used similar components to the original and a similar type of construction, the compensation components C1 and R7 in the oven controller should not need to be altered. If the thermal coupling between the heater transistor and the thermistor is changed substantially or the reference voltage is changed, you will most likely have to suppress oscillation in the control loop. I find in these circumstances that if you make C1 and R7 comply with the following equation, the loop will stabilise.

\[ F = \frac{1}{2 \pi \sqrt{C1 \cdot R7}} \]

where \( F \) is the frequency of oscillation of the loop.

I chose a value for C1 (1 uF) then worked out a value for R7 based on the above equation. This is certainly not a rigorous design based on control system theory but a “good enough” cut and try method.

With some rudimentary insulation over the board, say a folded up towel or other piece of cloth, the supply current should stabilise in about 4 minutes after a cold switch on and settle at somewhere between 50 and 150 mA depending on the insulation and ambient temperature.

Testing the oscillator section starts with setting R15 and C17 to about mid-range. Ensure that the regulator output voltage is close to 8 volts. Measure the output level with a diode probe or oscilloscope. I got about 8 dBm or 1.5 volts peak to peak into 50 ohms at the output. Mount the circuit board in the box, fit the insulation and you are ready to set the frequency.

Couple a little of this signal into a receiver tuned to WWVH on 10 MHz with the receiver set to USB, LSB or CW. Adjust the BFO for a note at a comfortable audio frequency. Adjust the coupling of the oscillator so that you hear the audio beat note itself beating at the frequency of the difference between the oscillator and WWVH. You should then be able to adjust the oscillator for zero beat with the Time and Frequency Standard signal.

Components

Some comments on component selection will assist those wishing to duplicate this reference oscillator. Many of the components in this design were selected as they were in the junk box which has been swelled considerably in recent years by the wealth of electronic equipment of many types being available at low prices or being given away or thrown out. Therefore where I have used a specialised component because it was on hand I will endeavour to give a commonly available substitute.

Oven Controller:

The reference diode LM329 is available from Farnell (Cat # 411-530). A zener diode would do as the bridge output differential is not very sensitive to the supply voltage on the bridge. 5.1 volt zeners have the lowest temperature coefficient.

Thermistor - could substitute 100 k device (Dick Smith R1797) change R2 to 33 k. I have a few spare 220 k thermistors if you are stuck.

Opamp is non-critical. Any single or one of a dual opamp will do, FET or bipolar input. Suitable alternatives to the 741 are LF351, TL071, TL072, LM358 etc.

C1 should be a plastic film capacitor, non-polarised.

TR3 can be any TO-220 or TO-218 PNP transistor but don’t use one with a fully insulated tab.

The copper heat spreader on which TR3 and the crystal and other components are mounted is a 60 mm length of 25 by 3 mm copper bus bar. Aluminium bar could be substituted but aluminium has half the thermal conductivity of copper.

Oscillator components

Crystal. This is the key to the oscillator stability but I thought that I could get good enough stability if I used a crystal of unknown source from the junk box. If you want the best stability though, a crystal should be ordered especially for oven operation at the temperature of the oven. In my case this is 60 deg. The oscillation mode is parallel, 30 pF capacitance.

Varicap. Almost any reverse biased diode will give enough frequency variation but a varicap proper will have
a higher Q. 1N914’s and even power diodes such as the 1N4001 series have been used as varicaps. There are lots of varicaps available in old TV tuners, FM radios and the like so there shouldn’t be a need to resort to using a power diode.

Transistors. The 2N5770 is a 2N706 with tighter specs but the latter could be substituted. BF199F (Altronics Z1106) would work and at these frequencies the BC547 would probably work as well, as would the 2N2222 or PN2222. A plastic case transistor is to be preferred as the metal case devices usually have the collector connected to the case. Dual gate mosfets, which could be substituted, are MFE131, BFR84 or BF981. A BC 547 could be substituted for the output emitter follower.

### Performance
- Output Frequency 10,000,000 kHz (adjusted)
- Warm up time: Frequency within 1 Hz after 4 minutes
- Frequency drift: Of the order of 0.2 Hz per day (2 X 10^-8)
- Output signal level 8 dBm
- Power consumption: 12 volts DC at 350 mA warm up for 4 minutes
  140 mA at 25°C ambient

### Conclusion
A 10 MHz oven controlled reference oscillator suitable for home construction is described. The oven temperature controller is of the proportional type and some hints have been given to achieve stability in the control circuit. The best frequency stability of the oscillator was not sought in this instance as it is intended that the oscillator be locked to the horizontal sync pulses of a television signal. A method of construction is described which does not involve the etching of a PCB.

### References

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**Remembrance Day Contest**

The War in the Pacific ended on 15th August 1945. Many Radio Amateurs served in the Services, both on active duty and at home. Some never returned from service. The Remembrance Day Contest is held on the weekend closest to the 15th August each year as a mark of respect to those who died.

When we look back at the sacrifice of our servicemen and women and of civilians, who stayed behind enemy lines and died, we acknowledge the debt we owe them for our continued democratic way of life in Australia.

However at such times it is also good to look forward and hope we have learnt something from these sacrifices. So this year I have chosen to focus on the present and the future and focus attention on the signallers of today. The pictures on the cover and with this article show how we now have both men and women in the field. They are still awfully young. Some of their equipment is still backpack and whip aerial, but more of it is computer keyboard and monitor screen. The frequencies used are higher as well and satellites are important links in the total system.

Let us not forget the past, but let us make sure we have learnt from the lessons so dearly paid for and we apply them to the future.

**LEST WE FORGET**

Photographs from Captain Sandra Turner of 9th Brigade, the Army Reserve Unit in SA and Tasmania. The personnel are all members of 144 Signal Squadron. Pte Kathryn Thomas took the photos.

I wish to thank them all for their contribution to our annual act of Remembrance.