The Denwood Matchbox Oven, Mk III

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Preamble

The author has been making and using temperature controlled chambers for many years. This is the third of a series of recent designs, and probably the simplest and best. These units are called 'Matchbox Ovens' because the original idea was to tuck the device needing temperature control into a humble matchbox. This current design can be used to hold any small device at a constant temperature, or can be set to incremental temperatures in order to study the device behaviour.

The first of these designs, the Mk I Matchbox Oven, used a micro-controller and I^2C temperature sensor, and was arguably the most complex, as it was part of a larger project being developed by Andrew ZL1WJQ. The idea was to control the temperature of an Si5351 fractional-N digital synthesiser. It had been discovered that superior stability, more than two orders better than the device achieves at room temperatures, was possible by using a small oven to control the device temperature. Some MEPT (QRP transmitter) applications, especially on the higher frequency ham bands, require a level of stability that is difficult to achieve without oven control.

The Mk II Matchbox Oven utilised a similar temperature controlled chamber, but used a stand-alone digital controller, based on the ubiquitous NE555 oscillator chip. The intention was to provide stand-alone oven control that could be independent of the host application, and thus more universally applicable. While successful, it was still unnecessarily complex. The Mk I and Mk II designs used a resistance heater and hand-made oven box, which meant that construction required considerable effort.

In order to simplify matters further, this time the design uses a very simple analogue controller, and can be applied to any small aluminium box, using a transistor as the heater. The design uses a commonly available op-amp, a power transistor and an NTC thermistor sensor, and readily available components.

The oven chamber is no longer a matchbox, but an off-the-shelf die-cast box. The space inside is similar to that in a matchbox, with space for an Si5351 synthesiser board, an AD9833 DDS synthesiser, or any small target board.. Some of the examples given in this paper used packaged oscillators as the target board, in order to illustrate other uses for the design.

Background

Careful measurements have shown that the Adafruit Si5351 reference crystal has a hyperbolic frequency versus temperature behaviour, with a useful frequency minimum at around 52 °C. This suggests that its reference crystal may be a slightly modified AT-cut design. Standard AT-cut crystals are made by cutting the quartz into blanks with a controlled angle to the Z axis of the mother crystal, then processing them into wafers. Figure 1 illustrates the effect of slight changes to the crystal cut angle. Crystals for room temperature applications typically have a lower cut angle (35° 10'), while those intended for oven use might have a cut angle of 35° 15’, which will have a gentle frequency minimum at about 53 °C.

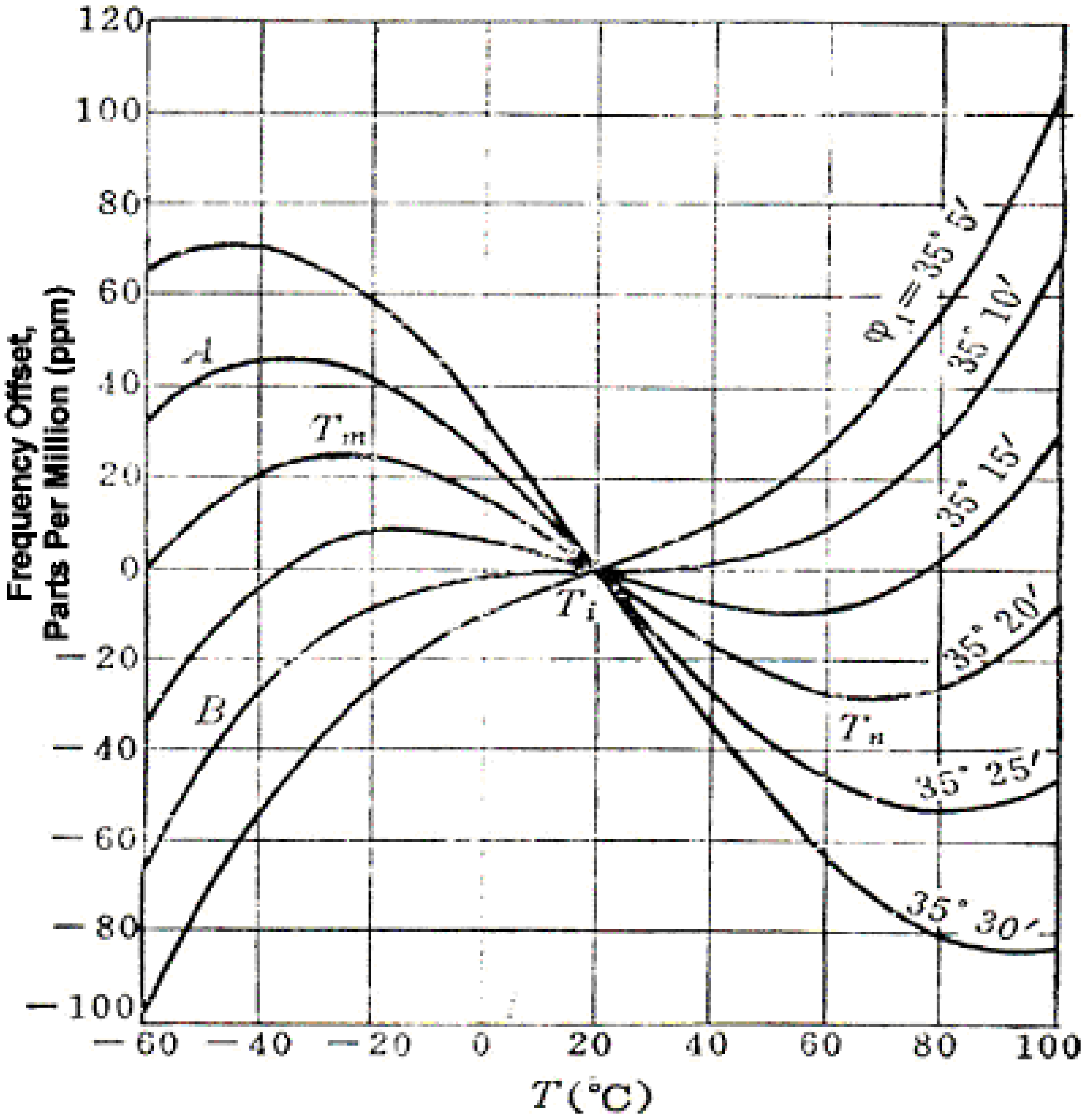


Fig. 1. Affect of relative cut angle of AT cut crystals.

Figure 2 (next page) shows the frequency versus temperature behaviour of an Adafruit Si5351 module, as measured in the Mk I Matchbox Oven.

It is clear that there is a minimum point at about 52 °C, i.e. the point at which, if the temperature increases or decreases, the frequency will increase, but if the temperature remains within a few degrees of the ‘sweet spot’ there will be little change in frequency.

At no other temperature will close temperature control give this level of stability. That is of course the motivation behind using a crystal oven, or in this case a whole-reference oven, the aim being to operate the crystal on the Si5351 module at this ‘sweet spot’.

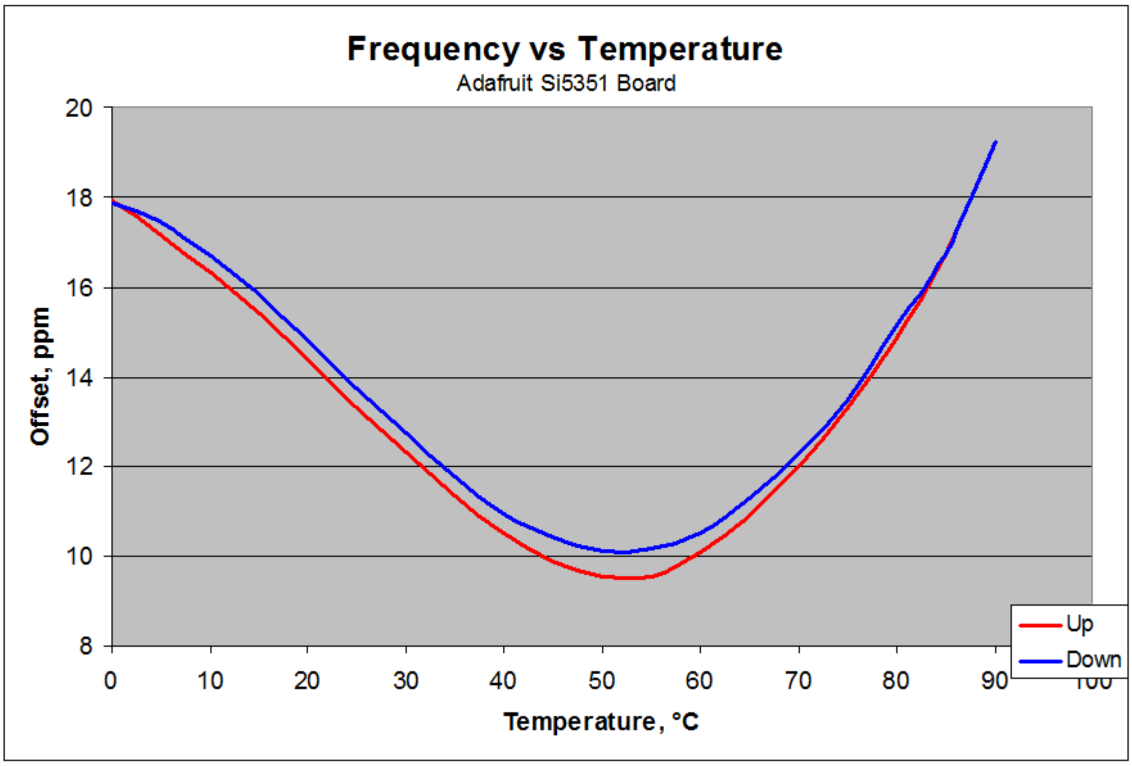


Fig. 2. Measured temperature characteristic of the Adafruit Si5351.

The measurements in Fig. 2 were made with the Si5351 output set to 10.001 MHz, beating in an AM receiver against a GPS Disciplined Primary Reference at 10.000 MHz. The resulting ~ 1 kHz audio was analysed using SBSpectrum, which can measure frequency to 0.01 Hz. You will note in Fig. 2. that there are two curves – one for increasing oven temperature, the other for decreasing oven temperature. This hysteresis effect is caused by temperature gradients across the crystal, inevitable if the temperature changes are made at or above 0.1°C/minute. To measure slower would take all day, and would be unnecessary, as the above graph tells the story quite clearly.

So the aim is to operate the crystal on the Si5351 module at the minimum frequency temperature, ± 1 °C, and thus yield frequency stability of perhaps 0.05 ppm p-p, maybe 1000 times better than the device achieves at room temperature. The Mk I oven easily achieved this, providing stability approaching $1e^{-8}$. It is expected that all Adafruit or Etherkit modules will have similarly cut crystals, although each individual device may need a slightly different temperature to achieve the minimum sweet-spot point, and this is taken into account in the simple set-up procedure.

While the use of the oven to control an Si5351 module has been described, the Matchbox Oven can be put to many other uses. One of course is to explore the behaviour of any suitable device over temperature, which can be done by adjusting the oven temperature, waiting until it is stable, then taking measurements before moving to another temperature. The Matchbox Oven III can be set accurately to any temperature in the range from just above room temperature to about 60 °C. Stability is easily within ± 1 °C. In order to make lower temperature measurements, the Matchbox Oven and its contents should be operated in a refrigerator, as was done for the test shown in Figure 2.

Design Description – Part 1

The Matchbox Oven Mk III (MB3) appears to be a simple arrangement, but it involves careful thermal and practical design, backed up by careful testing and evaluation. The space inside needed to be big enough for the Adafruit or Etherkit Si5351 modules, to allow for easy egress by the various leads, and provide the necessary electrical and thermal insulation from the surrounding metal box. The box is part of the thermal path to the device in the chamber, helping to maintain an isothermal environment for the device, which in turn limits any undesirable thermal gradients across the frequency determining components, thus providing superior thermal and stability performance.

The MB3 chamber consists of a small die-cast box, a Jaycar HB5030. A Bud CN-5700, Hammond 1590LB or another box of the same size (64 x 58 x 35 mm) would be suitable. On the floor of the box sits the heater controller, and above it is space for the 'Device Under Test' (DUT).

Fig. 3. The oven diecast box and heater controller.

Figure 3 shows the die-cast box before assembly, with the heater controller sitting inside. In the finished unit there is an 0.4 mm insulating layer under the board, and the power transistor is bolted to the end of the box with a mica insulator and thermal grease. From Figure 3, it's quite obvious that the remaining space inside the box is similar to the size of a matchbox. The controller board is secured by the transistor at one end, and a bolt and 2 mm fibre spacer secure it to the box bottom at the other end. Both bolts are countersunk and enter from outside the box. The controller board needs to be built small and quite shallow in order to provide enough height for the DUT.

The purpose of the metal box is to spread the heat from the transistor all around the enclosure, i.e. to promote an isothermal environment inside. This is why a heavy-walled box was chosen over a folded metal box. The heater is simply an NPN Darlington TO-220 transistor operated in a feedback loop with current limit.

By operating the heater controller actually inside the chamber, it too benefits from a constant temperature environment.

Figure 4 shows a typical DUT board (in this case a TCXO) fitted in the test space. It sits above a layer of 0.1 mm mylar insulation. Another similar insulator is fitted in the lid, held in place by double-sided tape.

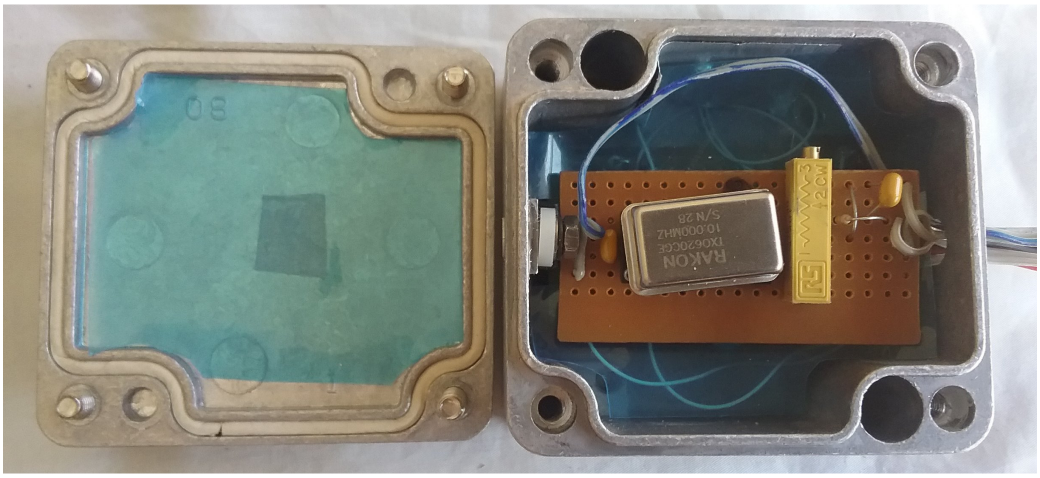


Fig. 4. The assembled chamber with DUT.

The test space will accommodate devices up to 50 x 30 x 13 mm, and is wide enough in the centre for 40 mm width if the board is appropriately shaped. The Etherkit Si5351 board is 50 x 30 x 4 mm, and the equivalent Adafruit board is just 30 x 20 x 4 mm. The test board in the photo is 50 x 25 x 10 mm high.

The oven is not complete without the outer insulation used to manage heat loss. The insulation also helps maintain the inner and outer surfaces of the die-cast box at the same temperature, and limits the effect of sudden changes in environmental temperature. When the chamber was first tested in open air, it required 130 mA (1.6 W) to achieve a steady 45 °C. Once assembled in the outer box, with insulation, this reduced to 70 mA (840 mW). The heater will easily manage sudden drops in ambient temperature, but without excellent insulation, sudden increases in ambient temperature (such as direct sunlight) could be beyond the controller without such good insulation.

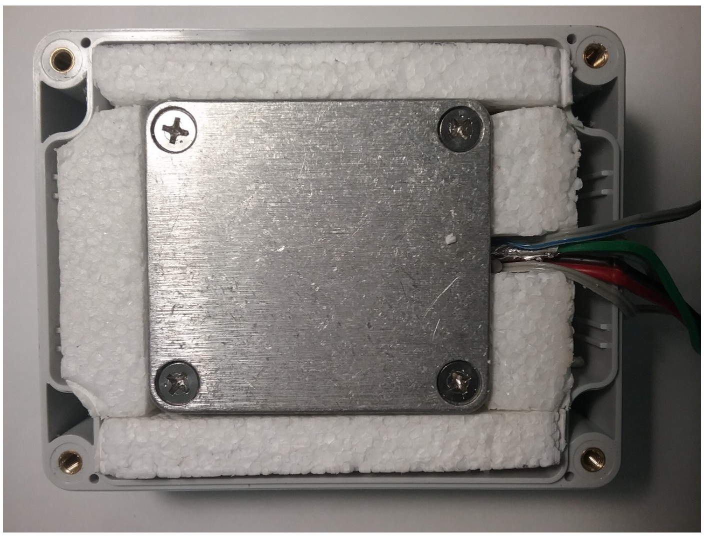


Fig. 5. The oven chamber and insulation.

The outer box is a Jaycar HB6216 Polycarbonate project box (115 x 90 x 55 mm). Figure 5 shows the assembled oven. There is a 10 mm base insulator of expanded polystyrene, four shaped side pieces, and another insulator in the lid of the outer box.

A comment about materials used in the oven: ***all*** components (electrical insulating film, aluminium tape, circuit boards, components and polystyrene insulation) have a temperature rating of at least 125°C, and so will be quite safe operating at up to 60 °C.

In Figure 5 the leads simply come out (to the right) between the outer box and the lid. In a fixed application, connectors could be fitted to the right-hand end of the box, as there is about 5 mm space provided. Spare lead length should be coiled up inside this space, as the longer the leads, the lower will be the heat loss from the leads.

Design Description – Part 2

An NPN Darlington power transistor (TIP121) is used as the heater. While it is mounted on one end of the box, the thick walls of the box and the excellent thermal insulation ensure that the heat is evenly distributed. Operating from 10 to 15 V DC, the 'heater' has a maximum power capability of 5 to 7 W. While the actual steady-state power required is under 1 W, the extra capability ensures fast warm-up. The power required depends on the ambient and target temperatures, on the quality of the oven insulation, and the heat loss in the leads in and out of the oven.

Figure 6 shows the Oven Controller. D1 provides reverse supply protection. R2 is the temperature set resistor (Rset), which can be permanently fitted, or an external variable resistor can be used. During project development, while looking for the optimum operating point, a resistor substitution box with 1% capability should ideally be used. The value for 53 °C is about 30 k Ohm.

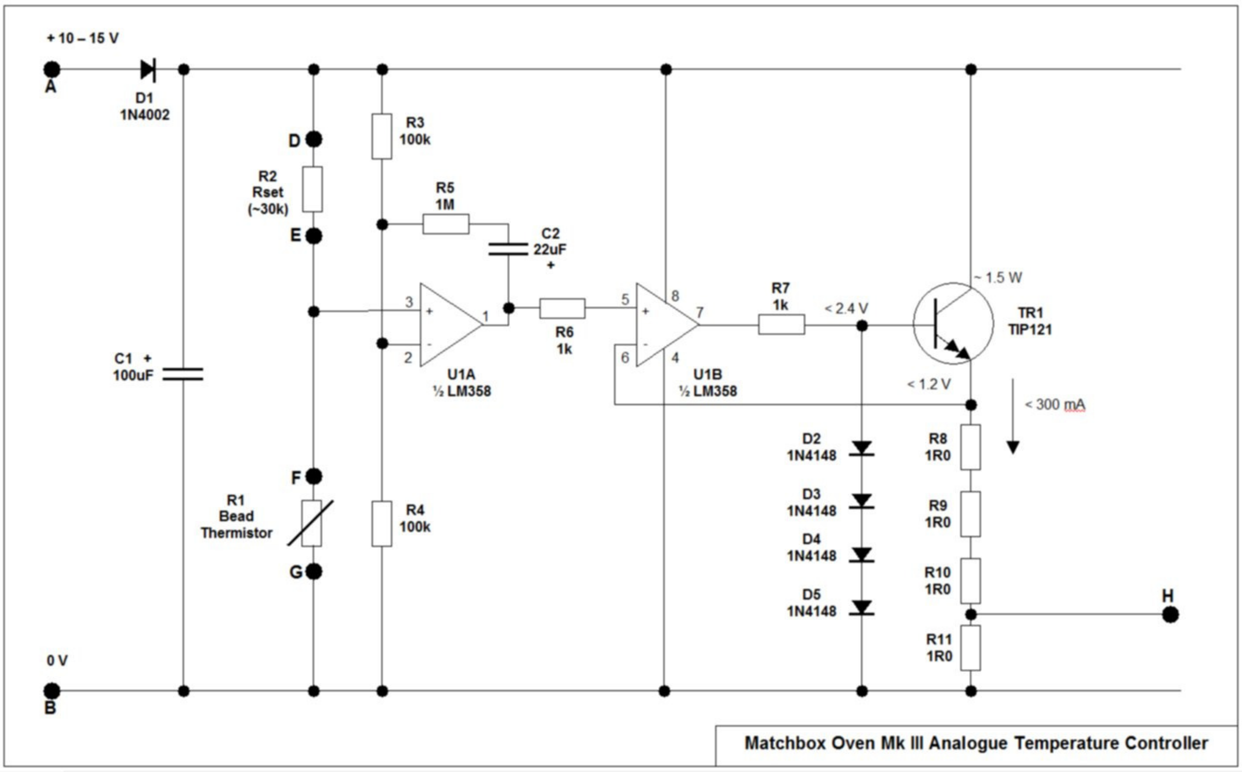


Fig. 6. The Oven Controller

R1 is a small 100k (at 25 °C) NTC bead thermistor, which is taped to the inner wall of the chamber. U1A operates as a bridge device, amplifying the difference between the Rset value and the thermistor with a gain of about 20, but with tantalum capacitor C2 in the feedback loop. The gain at very low frequency (similar to the oven time constant) is therefore infinite, eliminating any DC offset. In other words U1A acts as an integrator.

Because U1A inputs operate as a bridge, its operation is completely independent of power supply voltage over the specified design range, 10 to 15 V. You can move the supply from 10 V to 15 V, or *vice versa*, and see no change at all in the oven temperature or power. The unit can therefore be run off a battery.

U1B and the heater transistor TR1 operate as a DC amplifier with very high current gain. The tiny temperature differences detected by U1A are translated into current in the heating transistor. TR1 has a combined 4 Ohm total emitter resistance, which acts as a current sense, forcing the base of TR1 to rise as current increases. When the base reaches about 2.4 V, the four diodes D2 – D5 conduct, shunting further base drive, limiting the transistor current to about 400 mA. The test point H is a useful place to monitor the heater current (1V per amp), although using a 500 mA meter in the power lead is a much simpler solution, as no extra lead is required. If the Rset resistor is external, the thermistor voltage (and therefore temperature) can also be monitored from point E, the bottom of the Rset resistor.

Design Description – Part 3

Much of the design is not visible in the photos or the drawings, but hidden in the physical components used. The system gain of the controller, the heater power, the oven and target device thermal capacity, the thermal lag and thermal loss all play a part in the design. While in this case the design was to some extent empirical, it was based on long experience of similar designs, and of course on the Matchbox Ovens Mk I and II.

The best way to assess and thereby illustrate the resulting performance is to run a series of tests on the system. Figure 7 shows the performance of the system from cold.

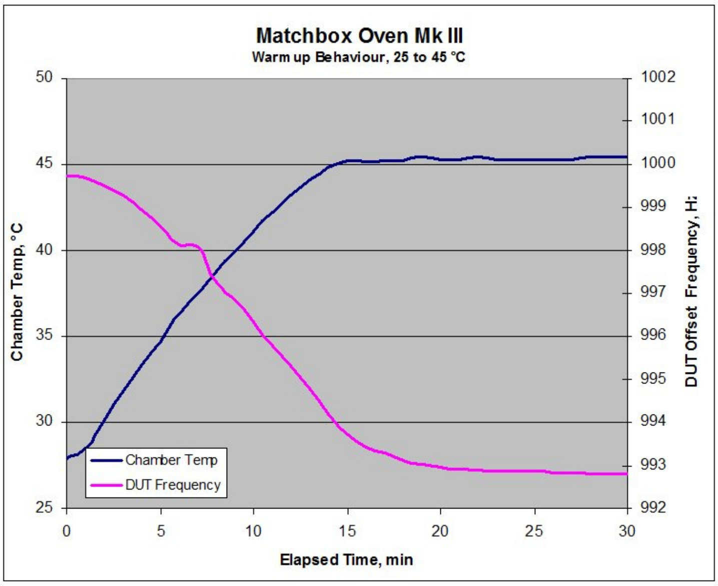


Fig.7. Temperature behaviour from cold start.

You can see in Figure 7 that while the control system is slightly overdamped, a stable temperature is reached within 15 minutes, with no oscillation or overshoot. (This was measured worst-case, without the outer insulation).

Overall stability can be assessed by pushing the controller off the stable temperature, then watching it recover. This is also illustrated in Figure 7, as the controller was told to go instantly from 25 °C to 45 °C. The other line on the above graph shows the frequency behaviour of a DUT (in this case a TCXO) as the chamber warms up. You can see that there is perhaps an extra 2 – 3 minutes delay as it follows the chamber temperature.

Construction

The mechanical aspects of the design have been well described already. All that remains is to describe the construction of the heater controller.

The controller was constructed on Vector Board (pre-drilled fibreglass board with 0.1 in spaced copper dots on the back). This was so the controller could be constructed in a minimum space. The same could be achieved using a small printed circuit board, laid out in the same manner as the grey tracks in Figure 8. (Resistors are shown in green, diodes purple, capacitors transparent green). Note that the drawing shows a *top view*.

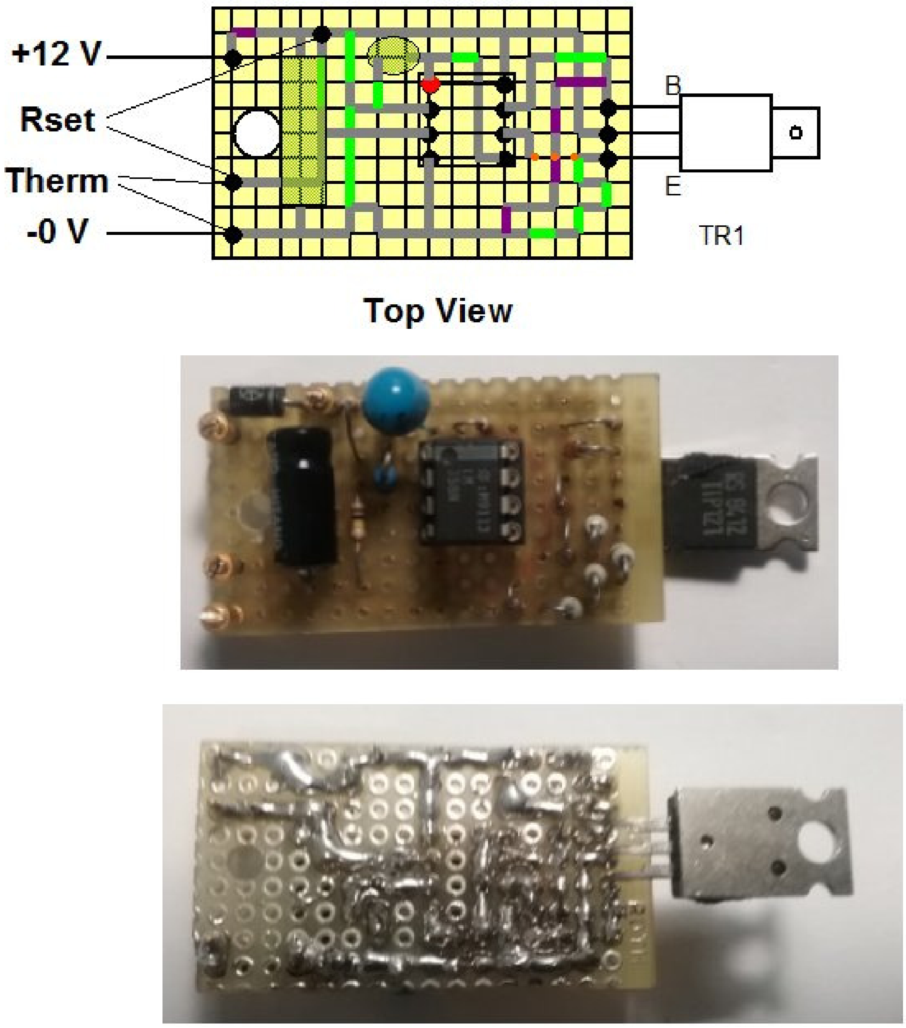


Fig. 8. Board layout (top), top side and bottom side photos.

It would be possible to construct the board from Veroboard, with the tracks running horizontally. With Vector Board (and considerable patience, dexterity and ingenuity), you can closely simulate a printed circuit board by ‘joining the dots’ with solder. In this design (Figure 8, top) there is only one jumper (shown dotted). Almost all the components are mounted vertically to save space.

Gold pins are used as connection points for external wires: power, Rset and the thermistor. A socket is used for U1, and during assembly C2 (blue capacitor in Figure 8 top view) is folded over the edge of the board, while TR1 is soldered to the back of the board and bent over the end of the board toward the component side. All the resistors used are 0.1 W, except R8 – R11, which are 0.25 W (each dissipates about 125 mW peak). Remember that components such as resistors need to be de-rated to operate at +60 °C.

Setting Up

This description is specifically aimed at an Si5351 target device, as a permanent installation, but it also applies to any oscillator to be operated at the crystal minimum point. Be sure to label all the leads clearly before going further. Once the Si5351 module is installed in the oven and the covers and insulation replaced, the leads to the controller and the DUT can be connected. Then connect the Si5351 to its controller and fire it up. You are then ready to set up the Matchbox Oven.

Initially, replace Rset with a 10 k resistor in series with a resistor substitution box. If you don’t have a substitution box capable of 1k Ohm steps, use instead a 50 k pot, preferably a 10-turn pot. Set the combination to 30 k Ohm, which represents about 53 °C.

Apply power, and set the Si5351 to a frequency of approximately 10,001.000 kHz (it will shift as the device warms up). Warm up your ***traceable and stable*** 10 MHz reference (needs to be stable better than $1e^{-8}$, preferably $1e^{-9}$).

Note – you cannot use WWV as the reference, as its received signal moves around too much, and you won’t see the tiny shifts you are looking for.

Listen to both signals on an AM receiver set to 10 MHz, and adjust the level of both signals in order to achieve a decent noise-free beat note, which should be around 1000 Hz. An AM receiver is used so the stability of the receiver cannot affect measurements. Leave the system to warm up.

An alternative method, used by the author, allows any frequency device up to perhaps 30 MHz to be set up. A Rubidium Synthesiser (FEI FE-5650A) is set ~1000 Hz lower than the target device, but otherwise the process is the same, with a beat note from an AM receiver *et cetera*. Note – you must use a synthesiser with a ***Rubidium*** reference, as nothing else will be stable enough.

After 15 minutes or so, start SBSpectrum on a computer, receiving sound from the receiver. Once things are stable, adjust the Si5351 via the control software so the beat note is about 1 kHz. The actual value is unimportant, and will be taken care of in final calibration of your software. Operate SBSpectrum first at 20 Hz span, then at 5 Hz span, centre the signal, and watch for it to become stable.

Then make ***tiny*** changes to the Rset value, noting which way you change the resistor or turn the pot. Wait ten minutes, and if the frequency has increased, make a change slightly the other way. If it has decreased, make a slight change in the same direction. Wait another ten minutes, then repeat over and over, always looking for the lowest frequency. Hopefully it will be well within the range of the pot. In fact the combined total of the resistor and pot should be quite close to 30 k Ohm.

Make the final adjustment in really tiny steps, preferably 1k Ohm or less, and with SBSpectrum at 2.5 Hz span. You might find that at 2.5 Hz span the device keeps drifting one way or the other, which makes looking for a minimum a bit tricky. This effect is caused by crystal ageing, and should settle down in time. At this magnification you are looking at effects that are at or below the 1ppb level ($1e^{-9}$). Once you get to a point where 1k Ohm Rset steps cause no visible change in frequency, you're done! Turn off the power, remove and measure your temporary Rset, and replace it (inside the chamber) with a single resistor or combination of series or parallel resistors that give the measured value to within 1%. Metal film resistors should be used if possible.

You don't need to actually know the final operating temperature, just that you are operating at the optimum point. If you are interested to know what the temperature is, use your Rset value and refer to the graph in Figure 10 below.

At the normal operating temperature the sensitivity of the system to the value of Rset is about - 0.7 °C per 1k change in Rset.

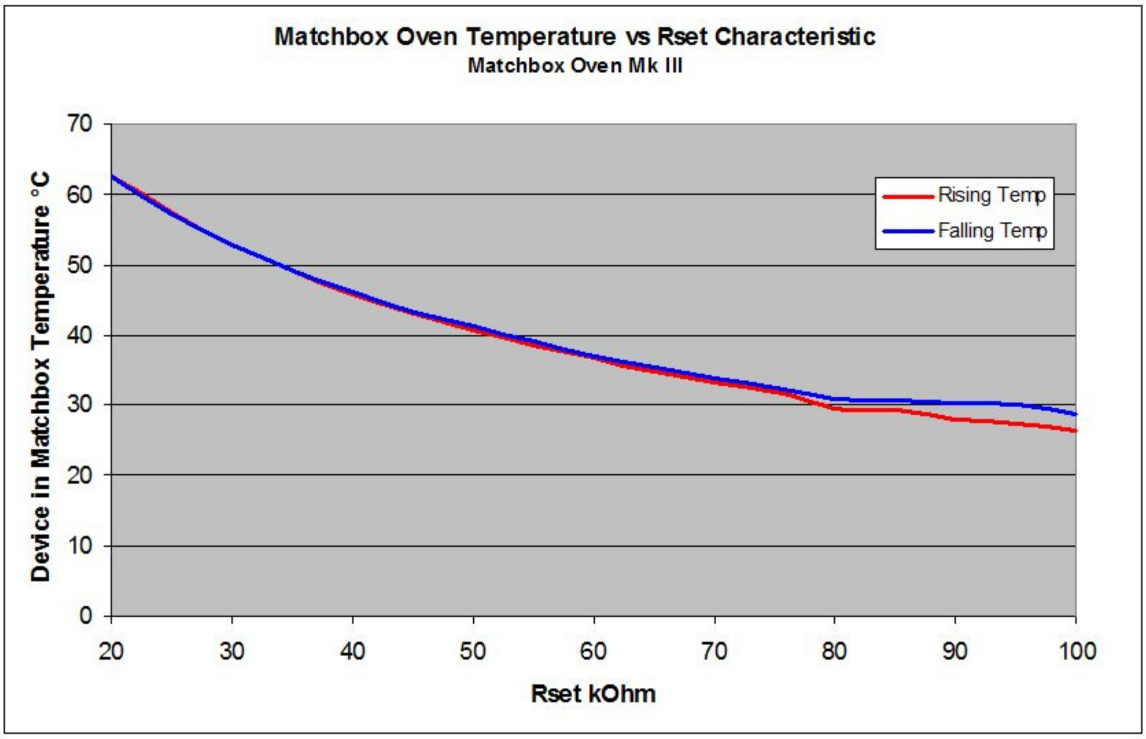


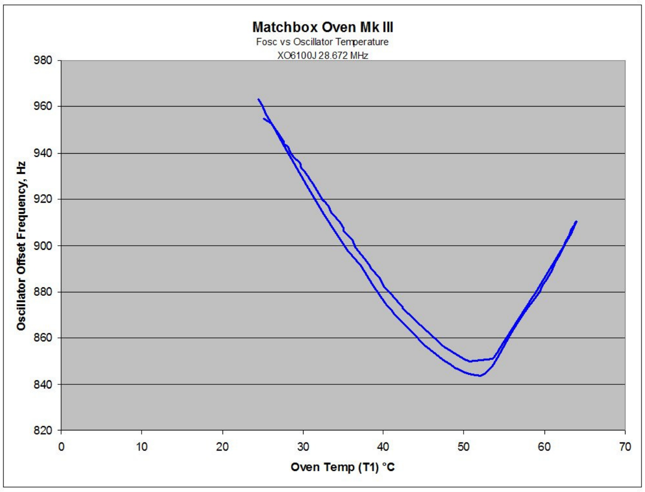
Fig. 10. Oven temperature vs. the value of Rset

Results

This design has achieved all that is required of a small test chamber, and can also be used to hold an AT-cut reference device at the minimum frequency temperature with no difficulty. Figure 11 shows an AT-cut crystal device (XO6100J, 28.672 MHz) measured in the MB3 chamber.

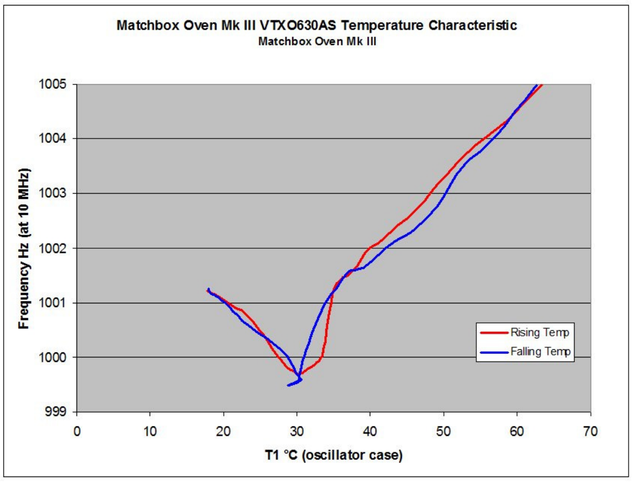
By operating the controller at stepped set points, a graph of the oscillator behaviour over temperature can be plotted. In figure 11 there are two curves, one for rising temperature, the other for falling temperature. The difference is caused by two effects: thermal lag between the device and the chamber, and internal thermal hysteresis in the crystal due to stress. Both of these can be eliminated by operating the oven more slowly.

This is a non-compensated device, and you can see that over the temperature range measured, the oscillator frequency varied by 4 ppm. Using the controller set to 52 ± 1 °C, using the set up procedure described above, this can be reduced to 0.03 ppm, or 30 ppb ($3e^{-10}$). Good stability by any standard.



Fig, 11. Typical uncompensated AT-cut device response.

Figure 12 illustrates another device, this time a 2 ppm 10 MHz TCXO, which if operated at the appropriate temperature (30 °C) would also yield ppb level performance. In this graph the upward and downward curves have been plotted in different colours.



Fig, 12. An unusual compensated device response.

The final photograph (Figure 13) shows part of the test set up during the MB3 development phase. A larger test chamber (in which the whole chamber under development could be heated of cooled) is not shown. Each item is annotated with a letter in **RED.**

Fig.13. Just part of the test set up!

A. Hewlett Packard 6205B dual power supply, laboratory grade. Used to power the DUT and the Oven.

B. Digitor Q1467 digital multimeter. Used to set supply voltages accurately, and measure thermistors and operating voltages.

C. Seven decade resistor substitution box, 1.5 Ohm to 9.999 M Ohm.

D. The chamber under development, in a temporary insulated box.

E. TASI-8620 dual-channel temperature meter, capable of 0.1 °C resolution. Uses small type K thermocouples.

F. Frequency Electronics FE-5650A Rubidium Synthesiser, modified by the author for remote control and operation from 100 Hz to 15 MHz. Used a PC serial control program written by the author, and an RS232 to USB adaptor.

G. JRC NRD-93 communications receiver, used in AM mode with AGC off to provide frequency offset as an audio output, for computer frequency measurement to 0.01 Hz resolution.

Summary

A device has been described which can deliver ppb-level performance from sub-ppm oscillators over a wide ambient temperature range.

The device has modest power consumption, and 12 V operation, so could be used in the field (say as a reference for 23 cm SSB operation), and is easily built using readily available components.

The unit can be used for fixed applications, such as to maintain an Si5351 module at the optimum temperature for best stability, or as a test chamber for development and measurement of oscillators and other small devices.

Appendix – Parts List

Mechanical

Jaycar HB5030 or similar die-cast aluminium box
Jaycar HB6216 or similar polycarbonate box
TO-220 mica insulator, thermal grease and mounting hardware
Misc. M3 nuts, countersunk bolts, washers, lock washers and spacers
Mylar film, 0.1 mm
Expanded polystyrene sheet, 10mm and 12 mm (cut from unwanted packaging).
Misc. wire, using ribbon cable for all but the heater power
Vector board, 50 x 25 mm

Electrical

C1	100 uF 25 V aluminium electrolytic, 125 °C rated
C2	22 uF 15 V tantalum electrolytic, 125 °C rated
D1	1N4002
D2, D3, D4, D5	1N4148
R1	100 k miniature bead NTC thermistor, TDK B57861S0104F040V24, Digi-Key 495-2143-ND (Jaycar RN3446 is suitable)
R2	~ 30 k metal film, select on test
R3, R4	100k 0.1 W metal film
R5	1 M 0.1 W metal film
R6, R7	1k 0.1 W
R8, R8, R10, R11	1R0 0.25 W metal film
TR1	TIP121 or similar NPN Darlington bipolar transistor
U1	LM358 dual op-amp
A, B, C, D, E, F, G, H	10 mm Vero test pins.