Oakley Sound Systems

5U Oakley Modular Series
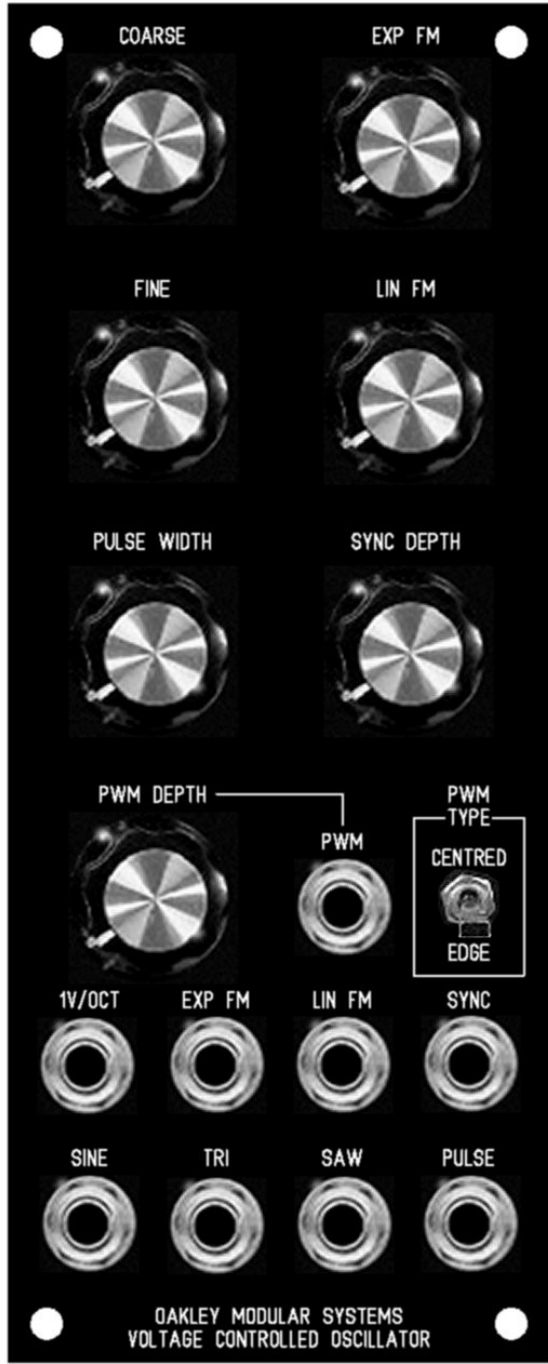

Voltage Controlled Oscillator

PCB Issue 7

Builder's Guide

V7.7

Tony Allgood
Oakley Sound Systems
CARLISLE
United Kingdom

COARSE

EXP FM

FINE

LIN FM

PULSE WIDTH

SYNC DEPTH

PWM DEPTH

PWM

PWM
TYPE

CENTRED

EDGE

1V/OCT   EXP FM   LIN FM   SYNC

SINE   TRI   SAW   PULSE

OAKLEY MODULAR SYSTEMS
VOLTAGE CONTROLLED OSCILLATOR

Introduction

This is the Project Builder's Guide for the issue 7 VCO 5U module from Oakley Sound.

This document contains a basic introduction to the board, a full parts list for the components needed to populate the boards, a list of the various interconnections and a description of the schematic.

For the User Manual, which contains an overview of the operation of the unit, the history of the various board issues, and all the calibration procedures, please visit the main project webpage at:

http://www.oakleysound.com/vco.htm

For general information regarding where to get parts and suggested part numbers please see our useful Parts Guide at the project webpage or http://www.oakleysound.com/parts.pdf.

For general information on how to build our modules, including circuit board population, mounting front panel components and making up board interconnects please see our generic Construction Guide at the project webpage or http://www.oakleysound.com/construct.pdf.

The Issue 7 Printed Circuit Board Set
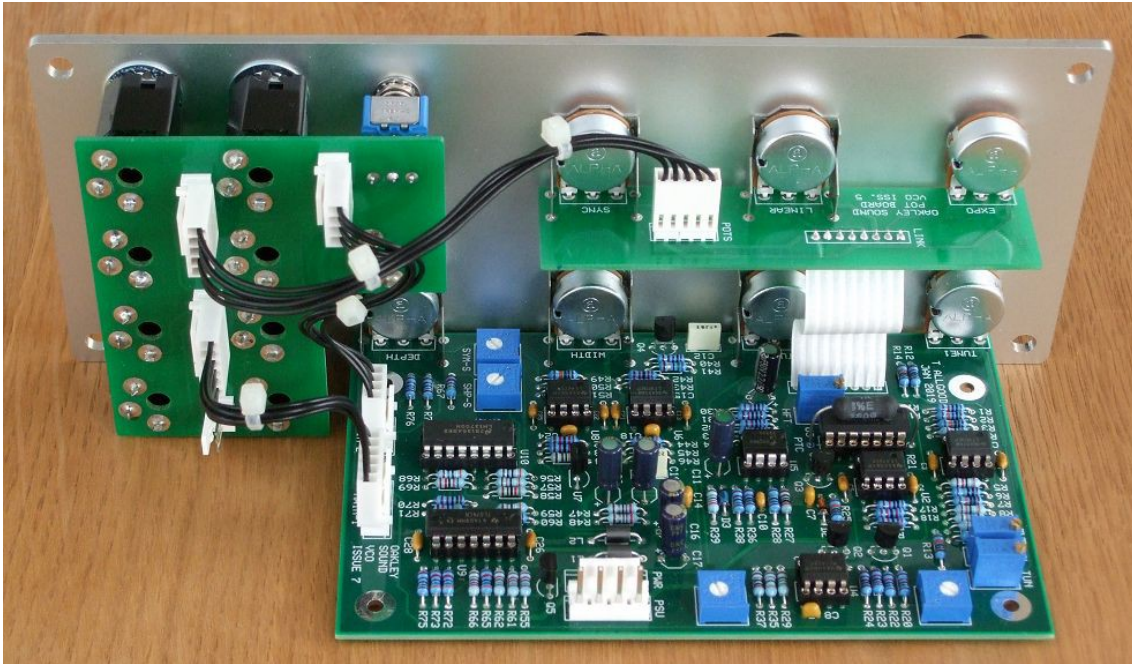
The issue 7 main board PCB with issue 5 pot and socket boards fitted to a natural finish Schaeffer panel. The board interconnects are Molex KK 0.1" types.

The main PCB is 89 mm (depth) x 143 mm (height) in size. The main board is a four layer design which means it has copper tracks on both the upper and lower surfaces as well as two internal layers. The upper internal layer is designated solely to 0V. The pot and socket boards use double sided boards with copper on the two outer surfaces.

If you are building the standard design, with the exception of the PWM switch, there are no components mounted off the boards. All components including sockets and pots are soldered directly to the boards. All the socket wiring can be done via the socket PCB and two MTA100 or Molex KK100 solderless connections. This system will reduce assembly time and possible wiring errors.

Some people will wish to use this Oakley design in a non standard format, such as fitting it to another manufacturer's rack or one of their own invention. This is perfectly easy to do. Simply do not use the socket board and wire the main board to the sockets as per usual.

I have provided space for the four main control pots on the PCB. If you use the specified 16mm Alpha pots and matching brackets, the PCB can be held firmly to the panel without any additional mounting procedures. The pot spacing is 1.625" and is the same as the vertical spacing on the MOTM modular synthesiser and many of my other modules.

The Temperature Coefficient Resistor

The positive temperature coefficient (PTC or temp co) resistor is a very special part. The ones I recommend are 1W wirewound resistors with a nominal TC of +3500ppm/K. You can buy these from Oakley Sound, KRL-Bantry in the US, or from Thonk. They are often sold as equivalents to the old Tel Labs Q81 series which was used in the VCOs and VCFs of many vintage synthesisers.
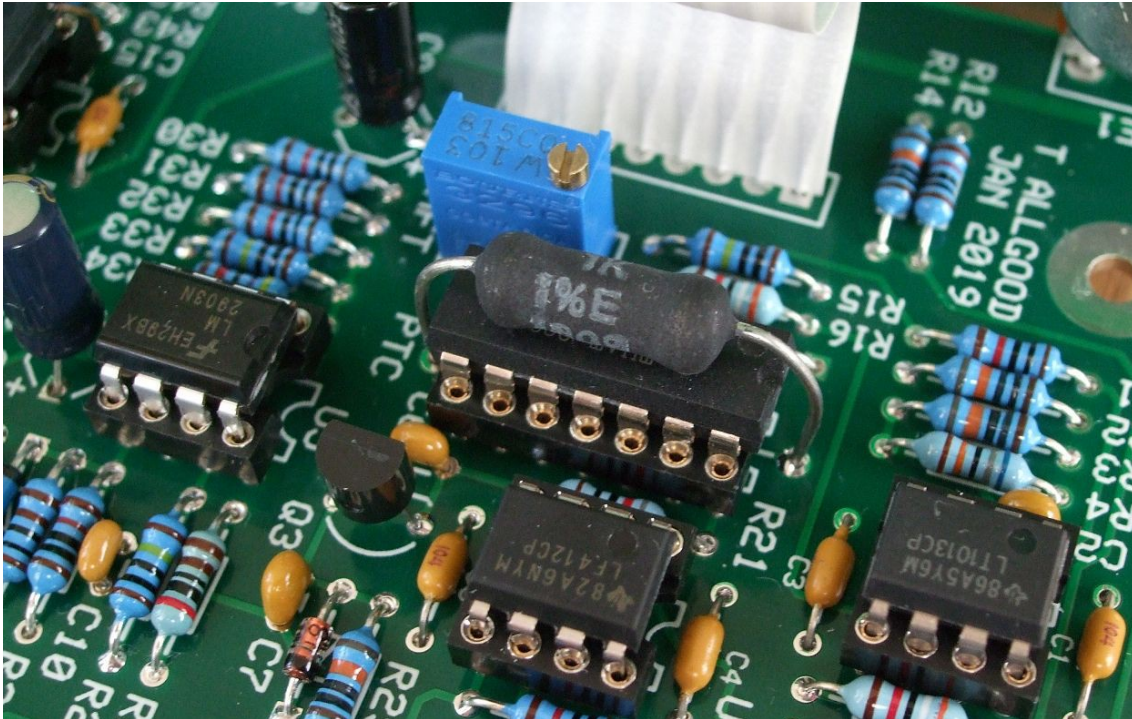
A close up of the exponential convertor on the issue 7 VCO. The THAT300 NPN array is mounted in a 14-pin DIL socket and the 1K KRL temperature coefficient resistor straddles it.

The PTC resistor is fitted to the board so that it lies across the top of the THAT300 NPN array. A bit of thermal compound (eg. Thermpath) could be used to keep the two devices in contact. You'll need to carefully bend the legs of the TC to make sure it lies flat on the surface of the THAT300 and still fits through its solder pads.

Important: Some specimens of the THAT300 have exposed metal sub-frames at the top (just below the identifying notch) and at the bottom of the IC packaging. These tiny metal pieces are connected to the chip's substrate and in the VCO will be connected to ground. It is essential that these metal surfaces do not come into contact with the PTC's leads. Unfortunately, this is quite possible as they reside close to where the leads come down past the THAT300's body. Please ensure that the leads do not touch the THAT300's package on their way down to the PCB.

VCO issue 7 Parts List

For general information regarding where to get parts and suggested part numbers please see our useful Parts Guide at the project webpage or http://www.oakleysound.com/parts.pdf.

The components are grouped into values, the order of the component names is of no particular consequence.

A quick note on European part descriptions. R is shorthand for ohm. K is shorthand for kilo-ohm. R is shorthand for ohm. So 22R is 22 ohm, 1K5 is 1,500 ohms or 1.5 kilohms. For capacitors: 1uF = one microfarad = 1000nF = one thousand nanofarad.

To prevent loss of the small '.' as the decimal point, a convention of inserting the unit in its place is used. eg. 4R7 is a 4.7 ohm, 4K7 is a 4700 ohm resistor, 6n8 is a 6.8 nF capacitor.

Resistors

1% 0.25W metal film types are recommended for all values.

22R	R39, R47, R48
75R	R41, R46
390R	R56, R68
820R	R21
1K	R38, R74, R76, R75, R40, R70
2K	R27
3K3	R54
7K5	R29
8K2	R58
10K	R36, R24, R31, R1, R12, R20, R60, R30, R64, R32, R17, R22
15K	R45
18K	R62, R55, R61
20K	R37
22K	R18, R19, R23, R42, R43, R52, R53
27K	R66
30K	R44, R26
36K	R72, R73, R65
39K	R16, R5
47K	R34, R71, R67
62K	R69
68K	R11
100K	R25, R13, R2, R49, R14, R51, R3, R7
180K	R50, R9*
220K	R63, R9*
390K	R8, R35, R57, R59
680K	R4, R10
1M	R33, R6, R28, R15

* For use with an issue 4 or earlier Oakley midiDAC, R9 should be a 180K 1% MF resistor.

* For use with a standard build issue 5 Oakley midiDAC, MU (Dotcom and others) and any

Eurorack system, then R9 should be a 220K 1% MF resistor.

1K +3500ppm/K   PTC – mounted on top of U3.

Capacitors

100nF 50V/63V axial multilayer ceramic	C5, C25, C4, C26, C21, C28, C3, C1, C13, C22

18pF C0G 2.5mm ceramic	C10
47pF C0G 2.5mm ceramic	C18
100pF C0G 2.5mm ceramic	C7, C27, C15, C24
220pF C0G 2.5mm ceramic	C14
470pF C0G 2.5mm ceramic	C2, C8
1nF C0G 2.5mm ceramic	C6

22nF, 63V polyester box	C19
100nF, 63V polyester box	C12

2u2, 63V radial electrolytic	C9
4u7, 63V radial electrolytic	C16, C17
22uF, 35V radial electrolytic	C23, C11, C20

Discrete Semiconductors

1N4148 silicon signal diode	D1, D2
BAT42 Schottky signal diode	D3

BC549C NPN transistor	Q1, Q2, Q4, Q5
J112 J-FET transistor	Q3

Integrated Circuits

LM13700 dual transconductance amp	U10
LM1458 dual bipolar op-amp	U4
LF412CN dual FET op-amp	U8
LM2903N dual comparator	U5
LM4040-10 10V precision reference	U7
LT1013CP dual bipolar op-amp	U1, U6
THAT 300 quad NPN array	U3
TL072 dual FET op-amp	U2
TL074 quad FET op-amp	U9

Trimmers

10K multiturn (eg. Bourns 3296W)	HFT, SCL
100K multiturn (eg. Bourns 3296W)	TUN

1K 6mm trimmer (eg. Bourns 3386F)	SHP-T
20K 6mm trimmer (eg. Bourns 3386F)	SHP-S
100K 6mm trimmer (eg. Bourns 3386F)	SYM-S, SYM-T

Pots

50K or 47K Linear Alpha 16mm	DEPTH, WIDTH, TUNE2, TUNE1 on main board EXP, LIN, SYNC on pot board
Alpha pot brackets	5 off

NB: If you have an older issue 5 Pot Board make sure you fit a slim washer in between the top pot on that board and the front panel. The extra washer acts as a shim between the pot body and front panel alleviating stress on the pot legs. The other two pots do not need this as they have pot brackets. Neither the main board nor issue 7 Pot Boards need this additional washer.

Miscellaneous

SPDT toggle switch	PWM type	1 off
3-way 0.1" header	Oakley Bus optional connector	1 off
Switchcraft 112APC	1/4" sockets mounted on socket board	9 off
4-way 0.1" MTA/Molex header	MAIN-2 (Main PCB and socket PCB)	2 off
4-way 0.1" MTA/Molex housing	MAIN-2 cable	2 off
5-way 0.1" MTA/Molex header	POTS (Pot PCB and socket PCB)	2 off
5-way 0.1" MTA/Molex housing	NSE cable	2 off
6-way 0.1" MTA/Molex header	MAIN-1 (Main PCB and socket PCB)	2 off
6-way 0.1" MTA/Molex housing	MAIN-1 cable	2 off
55mm 8-way jumper lead*	LINK interconnect	1 off
MTA156 4 way header	PSU – Oakley/MOTM power supply	
MTA100 6-way header	PWR – Synthesizers.com power supply	
Leaded ferrite beads	L1, L2	

* Suitable part number is TE Connectivity's FSN-22A-8.

You may well want to use sockets for the ICs. I would recommend low profile turned pin types as these are the most reliable. You need one 16-pin DIL socket, two 14-pin DIL sockets, and six 8-pin DIL sockets.

Wiring the sockets and switch using the VCO Socket Board

The general details of populating an Oakley socket board are given in our Construction Guide however there are a few extra things that are worth mentioning. You not only have the sockets and headers to fit but you also have a switch to attach to the socket board.


This is an Apem toggle switch mounted to a 3mm Schaeffer panel. Note the spring washer and nut behind the panel.

Once you have soldered your headers and sockets into place remove the socket PCB from the panel and fit your switch into the correct hole in the panel. Use the one of the nuts and the spring washer on the inside of the panel. Use the second nut on the front of the panel but don't tighten it up. Only thread it on so that all the nut is in place on the bush of the switch. Now use the inner nut to tighten the switch to the panel. This way you won't scratch the front of the panel. Use a 5/16" open ended spanner to do this but don't tighten it too much, it's only a little switch. It doesn't matter which way the switch goes in so long as the toggle moves up and down. Note you do not have to use the tagged washer that the switch normally comes with. Now solder a short length of thin uninsulated solid core wire to each of the three tangs. You can use some resistor lead clippings if you wish. Make sure the wire leads stick up at right angles from the panel surface.

Now refit the socket PCB with all of its sockets back onto the front panel. Carefully align the three wires from the switch through the three solder pads in the PCB. Now you can then flip the panel over and fit all the sockets' washers and nuts. Once this is done, you can solder the three switch leads onto the PCB. Clip off any excess lead length that sticks out above the solder.

Connecting the VCO pot and socket boards

The first thing that will need doing is the interconnection between the pot and main board. This is done with a 55mm long 8-way jumper connection. Simply thread all eight wires into eight holes of the LINK pads from the underside of the pot board. The other end of the jumper can then be gently coerced into the LINK pads of the main board. Solder each end of the jumper. You must solder the pot board from the top of that board, and the main board from the bottom of that board.
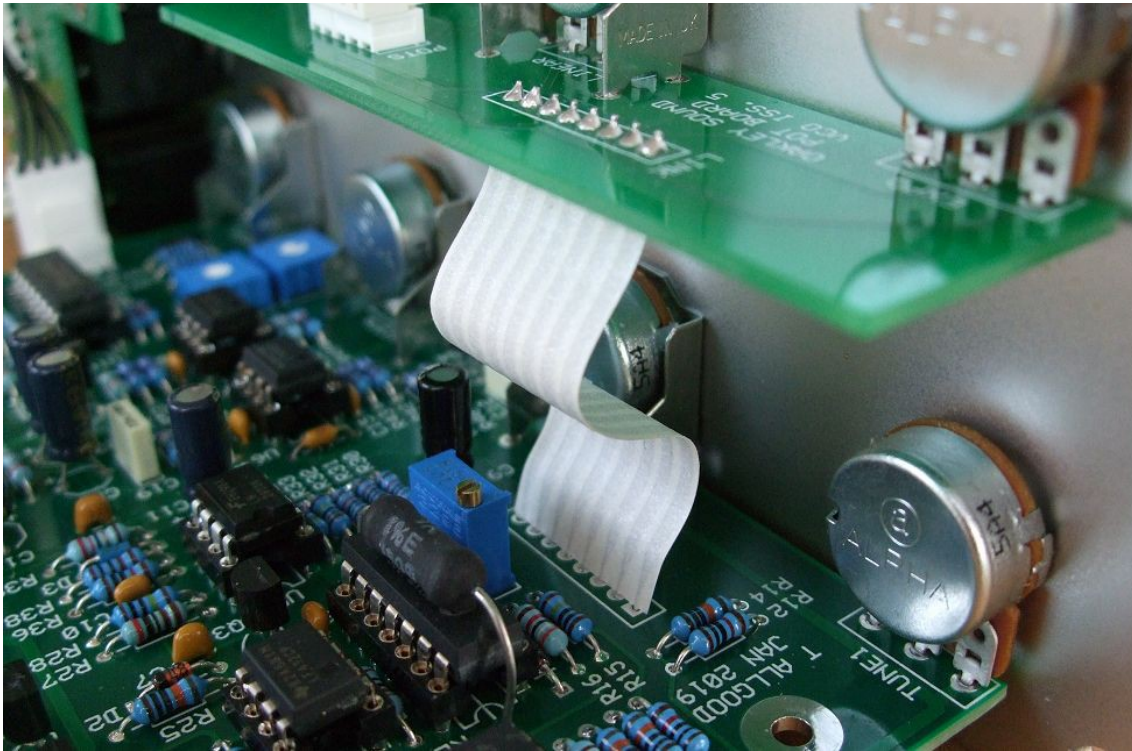
A close up of the 55mm long 8-way flexible interconnect between the main board and the pot board.

All the remaining interconnects will be made using either the MTA system or the slower, but cheaper, Molex system.

Make up the 4-way interconnect first. This should be made from wires 100 mm long. Make sure you get pin 1 going to pin 1 on the other housing, pin 2 to pin 2, etc. This cable will connect to the headers called MAIN-2 on each board.

The second lead is a 5-way interconnect. This is made up to be 145 mm long. This should connect the POTS headers on the socket board and the pot board.

The third lead is a 6-way interconnect. This is made up to be 90mm long. This will connect the MAIN-1 headers on the main and socket boards.

You can use some cable ties to bundle the wires in each interconnect together. This is best done once all the interconnects are in position.

Hand wiring the pots, sockets and switch

This will be a lot more complicated than using the special VCO pot and socket boards. There are a lot of connections to be made. However, if you take your time and use the schematic and this Builder's Guide to help, you shouldn't go wrong.

Pots

Fit the three pots to the front panel. I recommend that you fit the pots so that the pins face down but there is no specific reason for this other than this guide will have assumed you have done so.

Pots have three pins. For all the three pots, EXP FM, LIN FM and SYNC DEPTH, two of these pins will be connected to main PCB via the header, LINK, whilst the remaining one will be connected to the appropriate socket's signal lug.

CW is the 'clockwise' end of pot's resistive track (from the rear this is the left hand side with the pins facing down). CW is always connected to the socket's signal lug. This carries the input signal to the pot. CCW is the 'counter-clockwise' end of the pot. CCW is always connected to 0V and is the ground reference for the pot. The wiper carries the attenuated signal to the main board.

Pin 1 on the header is the square solder pad and is found at the top.

Connect the pots as follows:

1. EXP FM

CCW	Pin 1 of Link
Wiper	Pin 2 of Link
CW	Signal lug of EXP FM

2. LIN CV

CCW	Pin 3 of Link
Wiper	Pin 4 of Link
CW	Signal lug of LIN CV

3. SYNC DEPTH

CCW	Pin 5 of Link
Wiper	Pin 6 of Link
CW	Signal lug of SYNC

Sockets

If you have bought Switchcraft 112A sockets you will see that they have three connections. One is the earth or ground tag. One is the signal tag which will be connected to the tip of the jack plug when it is inserted. The third tag is the normalised tag, or NC (normally closed) tag. The NC tag is internally connected to the signal tag when a jack is not connected. This connection is automatically broken when you insert a jack.

Once fitted to the front panel the ground tags of each socket can be all connected together with solid wire. I use 0.91mm diameter tinned copper wire for this job. It is nice and stiff, so retains its shape, and you can make a neat framework that connects all the earth tags together. I would make it so that the lower four sockets are joined with one long horizontal piece, the top row of four sockets with another piece, and the PWM socket's earth tag the joined with a final vertical piece that straddles both the lower two horizontal rows.

A single piece of insulated multistrand wire can then be used to connect all those connected earth tags to pin 2 of the header labelled MAIN-2. Pin 1 is the square solder pad, so pin 2 is the one to the left of that when looking at the topside of the board.

All the other remaining socket connections are connected to the signal or NC lugs of the sockets. The tables below show the connections you need to make to the three headers, MAIN-1 and LINK:

MAIN-1

Pin	Pad name	Socket	Lug Type
Pin 1	Pulse	PULSE	Signal
Pin 2	Sawtooth	SAW	Signal
Pin 3	Triangle	TRI	Signal
Pin 4	Sine	SINE	Signal
Pin 5	Mod	PWM	Signal
Pin 6	1V/OCT	1V/OCT	Signal

LINK

Pin	Pad name	Socket	Lug Type
Pin 7	0V	1V/OCT, EXP FM	NC
Pin 8	0V	LIN FM, PWM, SYNC	NC

Switch

You should attach the switch to the front panel. Use the one of the nuts and the spring washer on the inside of the panel. Use the second nut on the front of the panel but don't tighten it up. Only thread it on so that all the nut is in place on the bush of the switch. Now use the inner nut to tighten the switch to the panel. This way you won't scratch the front of the panel. Use a 5/16" open ended spanner to do this but don't tighten it too much, it's only a little switch. It doesn't matter which way the switch goes in so long as the toggle moves up and down. You do not have to use the tagged washer that the switch normally comes with.

The switch has three lugs or tangs. Each one is to be connected to the main board using the three remaining empty solder pads on MAIN-2.

The top tang of the switch needs to be connected to pin 4 of MAIN-2. The middle tang to pin 1, the square pad. The bottom tang to pin 3. Keep these wires as short as you can.

Power supply connections

MOTM and Oakley

The PSU power socket is 0.156" Molex/MTA 4-way header. Friction lock types are recommended. This system is compatible with MOTM systems.

Power	Pin number
+15V	1
Module ground (0V)	2
Socket ground	3
-15V	4

Pin 2 on the MAIN-2 header is connected to pin 3 of the PSU header and has been provided to allow the ground tags of the jack sockets to be connected to the power supply ground without using the module's 0V supply. Earth loops cannot occur through patch leads this way, although screening is maintained.

MU and Synthesizers.com

The PWR power socket is to be fitted if you are using the module with a Synthesizers.com system. In this case you should not fit the PSU header. The PWR header is a six way 0.1" MTA, but the pin in location 2 is removed. In this way location 3 is actually pin 2 on my schematic, location 4 is actually pin 5 and so on.

Power	Location number	Schematic Pin number
+15V	1	1
Missing Pin	2	
+5V	3	2
Module ground (0V)	4	3
-15V	5	4
Socket Ground	6	5

+5V is not used on this module, so location 3 (pin 2) is not actually connected to anything on the PCB.

If fitting the PWR header and using it with a standard MU power distribution system, you will also need to connect together the middle two pads of the PSU header on the main board. This link connects the socket and panel ground with the module ground. Simply solder a solid wire hoop made from a resistor lead clipping, or bit of solid core wire, to join to the two middle pads of PSU.

If you are using an Oakley MU Dizzy distribution board with a five way power cable, the link on the PSU header is not required. This will allow the socket ground to be kept separate from module ground to prevent ground loops.

Circuit Description

The VCO circuit can be thought of as several little subsections connected together. Let us look at these little sections separately.

The first thing to look at is the power supply. This is shown on the bottom of the second sheet of the schematics. The VCO could have been powered by +/-15V, but I wanted the VCO to sound like a Minimoog. To do this, I have used the same voltage levels within the VCO core as the original. Thus we need to generate stable +10V, -10V and +5V supplies. These very stable voltages are also used to feed the pots and trimmers on the module to ensure that small changes in the power supply do not affect things like pitch and wave shape.

Power enters the board on a 4-way MTA156 connector (PSU) or modified six way MTA100 header (PWR). It is filtered initially by two small ferrite inductors, and decoupled by C16 to C17. These prevent very high frequency pulses from entering or leaving the unit by the power supply lines. A precision LM4040 reference diode, U7, is used to generate a very accurate 10V. This is inverted by a standard inverting amplifier based around U8 (pins 5, 6 & 7) to create a stable -10V. The +10V is generated by the circuitry around U6 (pins 1, 2 & 3) by inverting the -10V. Since the demand for current is greater from the +10V than from the -10V, Q4 acts as the output stage for the inverting amplifier.

Additional power supply decoupling is provided to each set of op-amps and ICs which is shown along the bottom of page 2 of the circuit diagrams. This keeps the power supplies to the op-amps relatively free of unwanted perturbations which could disrupt their behaviour. One of the big problems in systems with multiple VCOs is that of soft syncing. This is where one VCO module causes another to prematurely reset when its frequency is close to the other VCO. This stops VCOs from being able to develop that wonderful rich rolling beating when they are mixed and slightly detuned. Even some commercial synthesisers have this problem but it could have been avoided with careful circuit design and board layout.

The VCO core also requires a particularly solid +5V supply. This is provided by yet another inverting amplifier, this time with a gain of -1/2, based around U6 (pins 5, 6 & 7). This is shown on page 1 of the circuit diagram. R46 and C18 provide additional stability for the circuit.

The VCO's pitch is determined by a variety of sources. Two 1V/octave CV inputs, and two pots on the front panel, and a trimmer to set initial frequency. U1 (pins 5, 6 & 7) is built as an inverting voltage summer. It takes the voltages from the five sources and adds them together. The gain of the summer is set by the input resistors and R11 and the SCL trimmer. For the two 1V/octave inputs the gain is roughly -0.7. The SCL trimmer is adjusted to give a rise of one octave in output frequency when the keyboard input voltage goes up by 1V. The output of the CV summer is then fed to the exponential converter via a potential divider built from R16 and the positive temperature coefficient (PTC) resistor. The PTC resistor is often called the 'temp co' resistor.

The exponential converter is based around on half of U1 (pins 1, 2 & 3) and the quad NPN array of U3. The output of this circuit (at pin 14 of U3) is a current that is proportional to the exponent of the voltage applied at the base of the left hand transistor of U3. The circuit gives the VCO a sensitivity of roughly -18mV/octave, so R16 and PTC reduce the output of the CV summer to this level. PTC is a temperature sensitive resistor and its resistance will go up with temperature at a rate of 0.35% for every degree Celsius. This should counteract reasonably well the temperature effects produced by the semiconductor junctions in U3. To get the best temperature performance PTC is

mounted right on top of U3. This way the temperature of the two devices should be roughly the same.

It is possible to get an exponential response from a single transistor, but that has problems as Vbe, the junction voltage, changes with ambient temperature. The 'temp co' resistor cannot compensate for this type of change in the transistor's operating current. So the now classic circuit with two perfectly matched transistors, top half of U3, and an op-amp, U1, is used. Changes in the Vbe for one half of the transistor pair are mirrored in the other. The op-amp then matches the current in the first transistor with the same current in the other one. So the collector current in the first transistor will effectively control the collector current in the second. And it is the current drawn by the second transistor that controls the frequency of the VCO.

The op-amp method also has another bonus, it allows an additional current to be injected into the inverting pin of U1. This current will directly control the output current of the exponential converter. R3 allows an external CV to control this current. We now have a linear frequency modulation input, whose sensitivity is set by R3. Connecting this input to the wiper of a pot, allows you to control the sensitivity of this input directly from the VCO's front panel. D1 and U3 (pins 5, 6 & 7 – wired as a diode) act as voltage clamps preventing excessively negative Linear FM voltages from damaging the delicate base-emitter junctions of U3.

Note that this input is not a true linear input control. This VCO, and most other modular VCOs, do not have that capability. What we have here is a constant modulation index input. This is linear modulation, but not linear control. The precise description of this statement is probably beyond the scope of this document, but in a nut shell it means this: The linear input will not act with a strict volt per hertz relationship. That is, for every 1V, the output frequency will not rise by a fixed amount. But it will act so that any applied audio rate FM will create a constant depth of modulation on any given frequency controlled by the usual 1V/octave inputs. This means that for audio rate FM effects (clangs, bells and the like) you can get very good results using the linear FM input.

R4 has been chosen to set the operating frequency of the VCO at approximately 1kHz when the voltage at the base of the left hand transistor is zero. The exponential converter works at its most accurate when the voltage across the two bases is zero. And since the human ear is particularly sensitive to frequency changes at around 1kHz it makes sense to make the most accurate part of the VCO around this frequency.

The output of the exponential converter at pin 14 of U3 is a current. It is this current that controls the core of the oscillator. Contrary to popular understanding, the core of many VCOs is typically a linear CCO. That is a current controlled oscillator. A doubling of current to (or from in this case) the CCO will produce a doubling of output frequency.

The core of this VCO is a sawtooth oscillator. C6, a very stable C0G capacitor, is the master timing component that is charged by the output of the exponential converter. Since one end of C6 is tied to +5V, the voltage at the other side of C6 moves towards zero volts as current is 'sucked' out of it. The higher the current the faster the voltage drops. This voltage is 'sniffed' by one half of dual op-amp U2 (pins 1, 2 & 3), which produces a replica of this voltage at its output. Q2 aids the output of U2, as well as providing a suitable offset for the triangle generator circuit (see later).

U5 (pins 5, 6 & 7) is a comparator, and it is 'watching' the output of U2/Q2. When the voltage across C6 reaches 5V, the output of U5 (pin7), normally at -15V, suddenly flies upward towards +10V. This sudden level change passes through C7, and turns on JFET, Q3. This rapidly shorts out

C6, and the voltage across the timing capacitor drops to zero and both of its pins are at +5V once again. This means that the voltage at the input of U2 is also at +5V, and the charging process begins again. A small feedback capacitor, C10, around the comparator ensures that the FET is switched on long enough to completely discharge the timing capacitor, C6.

The sync input enables an external voltage to trip the comparator early. This will cause premature shorting of the capacitor, locking the fundamental of the VCO to an incoming external sawtooth signal. However, the fall time of the VCO's saw waveform will still be set by the input CV to the VCO. Thus, you will not get traditional sawtooth waveforms, but half completed sawteeth. The sonic affects of these are marvellous, especially if you sweep your VCO with an envelope generator whilst locked to another VCO at fixed frequency. The controlled VCO is often called the 'slave', while the fixed VCO is called the 'master'.

The incoming sync signal is first buffered by U9 (pins 1, 2 & 3) which is configured as a voltage follower. This is shown on the second page of the schematics. The buffered signal is then passed to a simple differentiator based around C14 (back on page one again). This part in conjunction with D3 and R36 only allow only fast moving rising edges of the input waveform to reset the VCO core. In theory this should also allow any pulse wave to be used as a sync input, but the best sync sounds are normally obtained when a falling sawtooth is used.

The Oakley VCO's front panel includes a depth control for the sync input. This will allow you to create partial syncing effects. This effect is very difficult to describe in words but very complex timbres can be produced this way.

At high frequencies the VCO can go a little flat due to the finite time it takes to discharge C6, and because of errors in the exponential convertor. By deliberating lowering the maximum peak voltage of the sawtooth waveform with R21, the capacitor has less charge to lose before the output of U2/Q2 reaches zero. The frequency is therefore higher than it would have been without R21. This works because the voltage drop across R21 linearly increases with increasing current from the exponential convertor. This method was first postulated by Sergio Franco, and is usually called 'Franco' compensation because of this. The method works very well, but it does mean that the amplitude of the sawtooth waveform decreases slightly with increasing frequency. In the first two VCO issues I made this resistor variable as I was using the Franco resistance to compensate for both the fixed discharge time and more variable errors in the exponential convertor. In later issues of the Oakley VCO, the Franco resistance was fixed and is compensating for discharge time only.

The exponential convertor causes errors due to 'bulk emitter resistance' or Rbe in the NPN pair, the top half of the THAT300. Now the THAT300 is a very good matched pair with relatively low values of Rbe, but it still has a significant effect when the VCO is being operated at high frequencies and the current through the convertor is relatively high. It should be noted that Rbe is not a real resistor, but it acts as if a resistor was connected in series with the emitter of the transistor.

As stated earlier, in the early issue VCO boards this loss of high frequency performance was cancelled out by the effect of the Franco resistor. But really, this is a bit of a kludge since the Franco resistor is designed to compensate for a fixed timing error (the FET discharge or reset time), whilst Rbe causes an error related to frequency. Over the limited range of an audio VCO, this is usually perfectly fine and the Franco method is used in many commercial synth VCOs as the only high frequency compensation technique. For issue three of the VCO I decided to go one better. I used a fixed Franco resistor for the reset time, but also used the Rossum technique to compensate for the exponential generator's error.

Dave Rossum, founder of E-Mu systems in the 1970s, was an important player in the development of the SSM chips. The SSM2030 VCO chip, although not as good in some ways to the later Curtis CEM3340, was ground breaking when it came out. Dave's method of high frequency (HF) compensation for the SSM2030 involved gently pulling the base of the first transistor of the NPN pair lower when the collector current through the second NPN gets bigger.

In the issue 3 Oakley VCO I slavishly copied Dave's idea as presented in Electronotes and indeed as implemented in the rev 1 and rev 2 Prophet 5. A fixed resistor connected between the matched NPN pair's emitters and the driving op-amp can be used to effectively measure the emitter current, since the voltage on its bottom end will fall as collector current rises. This voltage was then passed through a diode, to compensate for the base-emitter voltage drop (Vbe) of the matched pair, and a small proportion of the resultant signal was fed back to the base of the left hand transistor. This works well enough.

However, due to work done by René Schmitz, this simple method can be improved upon with the same number of components. The diode in the pure Rossum method doesn't exactly compensate for the Vbe because the current flowing in the diode and the base-emitter junction are very much different. In René's idea both semiconductors see a similar current as they are fed from identical resistive sources; in the issue 7 Oakley VCO you will see that R1 and the HFT trimmer are both the same value. Therefore, the voltage drop across the 'diode' and Vbe should track each other reasonably well, even over a change in ambient temperature. The 'diode' in the issue 7 VCO is actually the base-emitter junction of a spare NPN transistor from the THAT300 array. One of the other benefits of René's method is that we feed the base of the exponential transistor with a fixed high value resistor which was not true of the original Rossum technique. So now the resistance due to the HFT circuitry that the left hand transistor base 'sees' is pretty much fixed at the value of R15 only. Thus altering the HFT trimmer should not result in a significant change in the overall operating frequency of the VCO as it did in the old method.

Going back to the VCO core: The sawtooth output from U2/Q2 is amplified and voltage shifted by the circuit using the other half of U2 (pins 5, 6, 7) before being sent to the output. The final output is roughly +5V to -5V, ie. 10V peak to peak

The triangle shaper is essentially a full wave rectifier, whose operating point is about 2.5V. If the operating point is not exactly half the peak value of the sawtooth output of U5, then the triangle wave will have discontinuities in it. This leads to a slightly brighter or harsher sound than the perfect 'textbook' triangle waveform. SHP-T is a trimmer that allows precise enough adjustment in the operating point to eliminate these glitches.

The created rectified wave is filtered with R24 and C8, buffered by U4 (pins 1, 2 & 3), before being amplified, inverted and level shifted by the circuitry around U4 (pins 5, 6 & 7). The SYM-T trimmer sets the DC offset of the wave output to match that of the sawtooth output. The final output is again 10V peak to peak.

The sine wave shaper circuit, shown on page two of the schematics, acts upon the triangle wave output. The rounded peaks of the sine wave are created by deliberately overdriving the inputs of one half of U10, a dual operational transconductance amplifier (OTA). These devices are normally used as VCAs, but in this VCO it is merely acting as a soft clipping unit. The non linearities of the OTA's input stage being utilised to squash the top and bottom peaks of the triangle wave input. SHP-S adjusts the amount of overdrive and thus the quality of the sine wave. Since U10 gives a

current output, it must be turned into a voltage and this is done by U9 (pins 5, 6 & 7).

R69 provides a special negative feedback path within the shaper circuit. This increases the non-linearity of the whole stage at the critical peaks of the output waveform.

SYM-S provides compensation for any asymmetry in the input triangle wave and the OTA's own offset voltage. Any offset voltage means that the OTA will soft clip asymmetrically. By adding a small offset voltage of the opposite polarity to one of the input pins, we can cancel the effects of the offset. The sine wave created by this process does not give us a perfect textbook example of a sine wave. However, the wave is very low in harmonics and for musical uses it is adequate.

The pulse conditioner is also found on page two of the schematics. The first section of this is the CV summer and is based around U8 (pins 1, 2, 3). This circuit simply sums together the PWM (pulse width modulation) CV input and the voltage from the wiper of the Width pot. The output of the CV summer will go from around -5.6V to +5.6V when being controlled by the Width pot alone.

The pulse wave generator itself is based around the second half of the comparator, U5 (pins 5, 6 & 7). This compares either the triangle wave or sawtooth wave output with a voltage set by the output of the CV summer. If the waveform is higher than the voltage from the CV summer, the comparator's output goes low to -15V. If it is lower, the output goes high to 0V. Thus, the output is either -15V or 0V, and spends very little time in between. This creates a rectangular waveform, where the relative proportion of time spent high or low is controlled by the WIDTH pot and/or the external CV. If the width pot is set to its middle position, and no input CV is applied, the output waveform should be a square wave.

The output of the comparator is out of phase with the audio input. Q5 inverts this signal, so that the generated pulse wave will go high when the saw or triangle wave is high. It would be possible to generate the correct phase by simply wiring the comparator's inputs pins differently. Thus you wouldn't have to invert the output since it would already be the right way around. Earlier issues of the VCO, in fact, did this. However, this caused a less than perfect output waveform. The positive feedback provided by R33, which is needed for good comparator action, would cause a small amount of the sawtooth or triangle wave to be superposed to the output waveform. This was considered not to be a problem, but with later issues I decided to do things differently. And perhaps more correctly.

What follows after the comparator is, I think, unique to modular VCO design. The inverted output of the comparator is now summed with two voltages in U9 (pins 12, 13 &14). One comes from the +10V reference supply via R65. The other is the output of the CV summer. The former allows the -15V/0V output swing of the comparator to be normalised between +5V and -5V. The other allows the output to be offset against zero volts as the pulse width is varied. When the CV summer has zero volts at its output, the generated pulse waveform is a square wave. No additional offset is added and the waveform from U9's output moves between +5V and -5V. As the pulse width changes, then the output of the CV summer moves away from zero. This is added to the waveform and the pulse output waveform moves above or below zero volts.

Analysing this dynamically changing output reveals that the average output voltage is actually always zero. This is because the offset added compensates for the altering amounts of time the waveform spends in the high or low states.

The summing circuit also inverts the waveform, so once again, we create the wrong phase. A simple

op-amp inverter circuit, U9 (pins 8, 9, & 10) turns the pulse wave the right way round again. If you do not want this dynamically varying output signal, then all you need to do is omit R62.

The source of the audio source for the comparator comes from either the triangle or sawtooth waveforms selectable with a switch on the front panel. This selection is another unique feature of the Oakley 'One of three' VCO. Both will sound the same with fixed pulse widths. But, they do sound different when the width CV is modulated quickly.

Final Comments

If you have any problems with the module, an excellent source of support is the Oakley Sound Forum at Muffwiggler.com. I am on this group, as well as many other users and builders of Oakley modules.

If you can't get your project to work and you are in the UK, then Oakley Sound Systems are able to offer a 'get you working' service. If you wish to take up this service please e-mail me, Tony Allgood, at my contact e-mail address found on the website. I can service either fully populated PCBs or whole modules. You will be charged for all postage costs, any parts used and my time at 25GBP per hour. Most faults can be found and fixed within one hour, and I normally return modules within a week. The minimum charge is 25GBP plus return postage costs.

If you have a comment about this builder's guide, or have a found a mistake in it, then please do let me know. But please do not contact me directly with questions about sourcing components or general fault finding. Honestly, I would love to help but I do not have the time to help everyone individually by e-mail.

Last but not least, can I say a big thank you to all of you who helped and inspired me. Thanks especially to all those nice people on the Synth-DIY and Analogue Heaven mailing lists and those at Muffwiggler.com.

Tony Allgood at Oakley Sound

Cumbria, UK
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