A pulsed driver for testing semiconductor lasers and superluminescent light emitting diodes

This simple medium speed driver was constructed for convenient testing of various novel types of semiconductor laser and LED sources. It was not intended to provide ‘test instrument’ performance, but rather to rather to provide reasonable transition speeds (<100 ns) at relatively low cost. The output circuit is based around a MOSFET driver chip. The low cost and simple construction makes duplication straightforward. Six such drivers were constructed and proved simple and convenient to use.

The driver is housed in a small plastic enclosure, is battery driven (PP3, 9V) and has a built-in pulse generator with variable pulse widths and repetition rates. This is intended to reduce the light emitter power dissipation, so different mark-space ratios and pulse widths are used for different types of emitter. Furthermore, the peak output current is variable and the maximum values are internally preset, depending on emitter type. The unit can also be powered externally (240 V AC to 9 V DC adapter), can be triggered externally (positive edge TTL level) and provides a synchronisation output (TTL levels) as well as a back-matched analogue output proportional to the current through the emitter. A digital readout of peak current is provided, while the pulse width and the repetition rate are set on graduated controls. The maximum output current that can be delivered is 1A (in case of laser driver) and 200 mA (in case of LED driver), although these values are readily altered internally, up to a maximum of 2A.

The complete unit is shown in Figure 1, where the functions of all the controls and connectors are indicated.

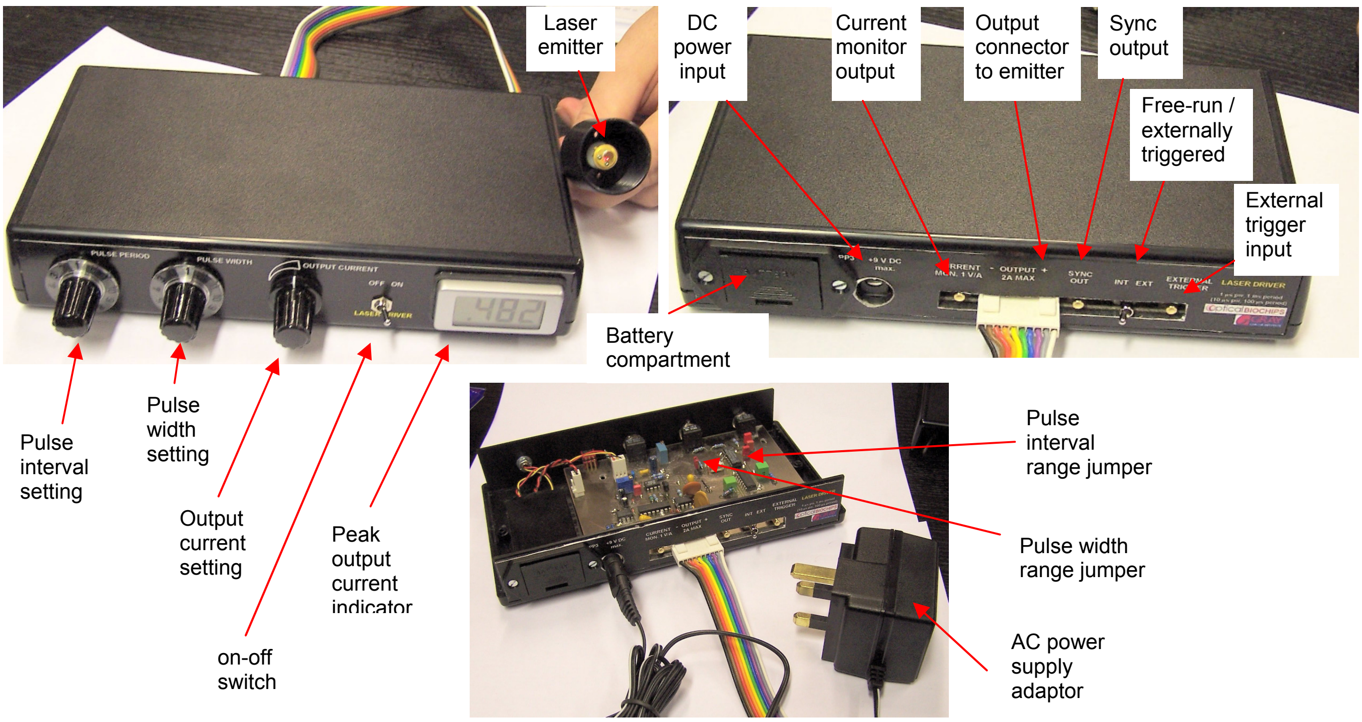


Figure 1: Front and rear views of the LED/laser driver unit. Further details of internal construction can be seen in Figure 4.

The drive pulse is provided by a MOSFET power driver which can supply currents up to several amperes with rise/fall times of typically <50 ns. The peak voltage produced by this driver is variable up to 17 V; this voltage is applied to the emitter through a current-limiting resistor and a current-sensing resistor (resistor values are preset for different emitter types). However, the finite lead length (and hence inductance) inevitably degrade the minimum rise/fall times and hence should be minimised. The ‘connections’ to the device are made through a 10 core ‘flat’ type cable, in order to minimise the inductance as much as possible.

The block diagram of the output stage is shown in Figure 2. The driver chip is a TC4429 driven by the pulse of appropriate width and supplied by a well-decoupled variable DC voltage derived from a potentiometer/operational amplifier. The supply voltage to the operational amplifier is produced by a voltage doubler (ICL7660) to 'boost' the limited battery voltage and allow driving of devices with a high forward voltage and/or slope resistance. The input to the operational amplifier (OP295) is derived from a front-panel potentiometer; two internal adjustments are provided to set the operating range of the pulse amplitude control: a fixed resistor is used to set the maximum pulse output voltage while a preset trimmer is used to set the minimum output voltage. Furthermore, the maximum output current can also be adjusted by changing the value of a series resistor (typically 10 Ω in the case of the laser driver, 56 Ω in the case of the LED driver). The pulse performance of the arrangement is not particularly sensitive to actual component values which can be readily modified to cater for devices of unusually high forward voltage or slope resistance.

The average current drawn from the battery is relatively low due to the low mark-space ratio of the output pulse current, and ranges typically from a few milliamperes to a few tens of milliamperes. In the case of the laser driver, the peak current is typically up to a 1 Ampere, dependent very much on the actual device used, and the mark-space ratio is nominally 1:1000, though it can be set to 1:100 with internal jumpers, i.e. 1-10 mA average. In the case of the LED driver, the peak current is typically up to 0.1 Ampere, and the M-S ratio is nominally 1:100, though it can be set to 1:10 with internal jumpers, i.e. again 1-10 mA average. In addition a quiescent current of some 10 mA is drawn by the rest of the circuit. With a PP3 battery, operation for a minimum of 10-20 hours is to be expected. As battery voltage falls, there is a gradual decrease of the maximum peak current that can be delivered, and this fact is obvious from the reading on the display/meter. Obviously the use of a mains-powered adaptor is recommended for use over extended periods. Nevertheless, it is only the maximum pulse current which is affected while other operating conditions remain unaffected by a falling battery voltage, down to around 6V.

The actual peak pulse current through the light emitting device is monitored by a current-sensing resistor which provides an output available on an SMB connector at the rear of the unit. This also feeds a peak detection circuit. The latter consists of a charging resistor (51 Ω), a fast switch (1/2 MAX4591) and an integrating capacitor. The relative delays through the switch and the TC4429 are such that the switch opens just before the fall time of the TC4429; the voltage stored on the capacitor is thus proportional to the 'integral' of the output current, with an integration time-constant of just over 40 ns, i.e. the shortest pulse width is readily captured. This voltage will decay relatively quickly through circuit leakage paths; it is thus buffered and re-sampled into a larger-value capacitor through a second analogue switch. However, because of the limited drive current capability of the buffer amplifier and its poor slew rate, the peak voltage on the second capacitor is reached some tens of microseconds later. The second switch sampling pulse is thus arranged to arrive at a later time, as provided by the timing logic. The final sampled voltage will in fact also decay, but with a much longer time constant, determined by the capacitor (47 nF) and a 100 MΩ shunt resistor, which forms part of a voltage divider, i.e. a time constant of around 5 seconds. The attenuated voltage (nominally 1 V for the maximum peak output current) is displayed on a 3½ digit voltmeter.

Care should be exercised when monitoring the output pulse current, available as a voltage sourced from a nominal 50 Ω at the rear of the unit. This output is back-matched and thus should not require termination by 50 Ω: any load at this point will inevitably affect the current calibration, particularly in the case of the LED model. This output should only be connected to a monitoring oscilloscope through a short (<1 m) coaxial cable.

The complete circuit of the driver is shown in Figure 3, where it can be seen that the logic/pulse generator sections of the unit are made up from two dual monostables. One of these dual monostables is normally configured as a free-running oscillator, providing the required mark-space ratio, as determined by front panel controls and by 'jumpered' capacitors. This arrangement allows the pulse width to be variable from 100 ns to 1.1 μs or from 1 μs to 11 μs (depending on the state of the jumper link) and the pulse interval to be variable from 100 μs to 1.1 ms or from 1 ms to 11 ms (depending on the state of the jumper link). Since the tolerance of the capacitors used in the timing monostables is relatively poor, the actual values are adjusted empirically at time of construction to conform to the specifications.

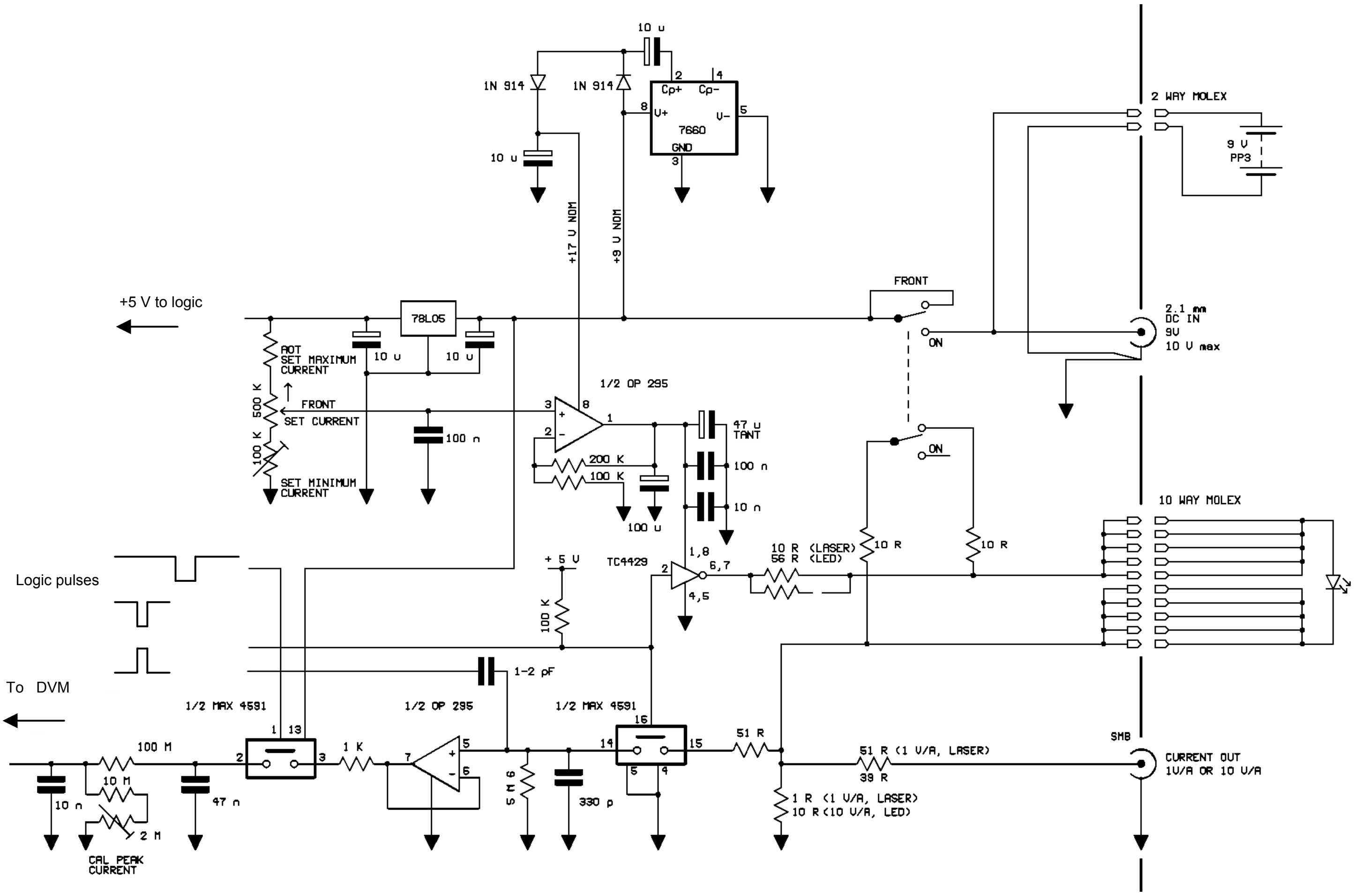


Figure 2: Output sections of the laser/LED driver. The operation of the circuit is described in the text. The optical emitter is short-circuited through a pair of 10 Ω resistors when the unit is 'off', preventing damage through ESD. Some charge feedthrough is inevitable in the fast peak-hold switch but can be compensated by injection of a complementary pulse through a 1-2 pF capacitor into the first peak-hold capacitor.

The feedback between the retriggerable monostables can be broken, using a rear-panel switch, to allow an external signal to trigger the pulse-width monostable. This input is a conventional logic (+5V) level and care should be exercised not to exceed +5V or supply voltages below ground. Only the 'pulse width' control is active under when 'external trigger' is selected. In addition, a 'sync' output is provided, able to deliver a +5V pulse into an open circuit, or around 500 mV into a 50 Ω load. This output is active in both internal (free-run) and externally triggered modes of operation. A second dual monostable provides a delay of around 60 µs before delivering an 8 µs sampling pulse to the buffered peak hold analogue switch; this delay is required to allow the buffer amplifier to settle to the required peak voltage.

A 'standard' single-supply DVM module is used to display the peak current reading. The input impedance of this device is reasonably high, allowing the use of a 100 MΩ voltage attenuator to provide a typical maximum meter f.s.d. of around 1V at the second switch output. Since there are inevitable losses in the peak-hold capacitors/analogue switches, the meter f.s.d. requires calibration, using a 2 MΩ preset. In practice, the 'zero' current reading/calibration is provided by adjusting the charge feedthrough capacitor (1-2 pF) while monitoring the readings and comparing to actual pulse current, as available on the current monitor output, while the 'top' end is calibrated by adjusting the preset. This procedure is repeated until an acceptable linearity/accuracy is obtained at both extremes of the meter reading. When properly calibrated the displayed reading should be well within +/-10 % of the actual pulse current, as monitored by a calibrated oscilloscope.

Figure 4 shows internal construction details and locations of calibration components and jumper links. It is important not to adjust the charge injection capacitor or the peak current meter calibration unless access to an oscilloscope to monitor the current output waveform is available. The maximum voltage and output current can be however varied by altering the appropriate resistor values.

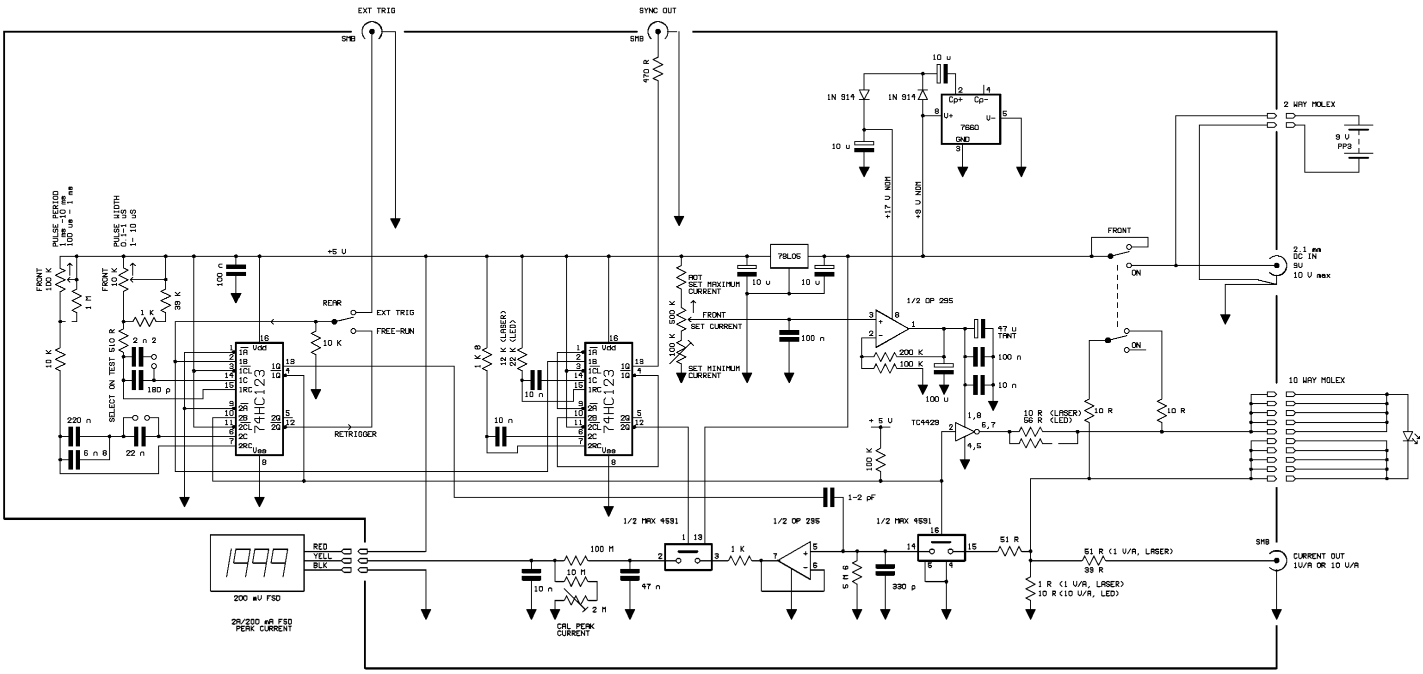


Figure 3: Complete circuit diagram of the laser / LED driver

Typical output pulse waveforms are shown in Figures 5, 6, 7, 8 and 9. It should be noted that the performance is affected by both the length of the output cable and by the dynamic performance of the emitter, particularly at the extremes of the output current range. Transition times of <30 ns can be readily obtained under optimum drive conditions, though <50 ns is more typical. In particular, at low currents, and where a device has a 'soft' turn-on characteristic, it is not unusual to observe a significant delay in the turn-on. Whenever possible, simultaneous monitoring of the optical emitter output should be undertaken.

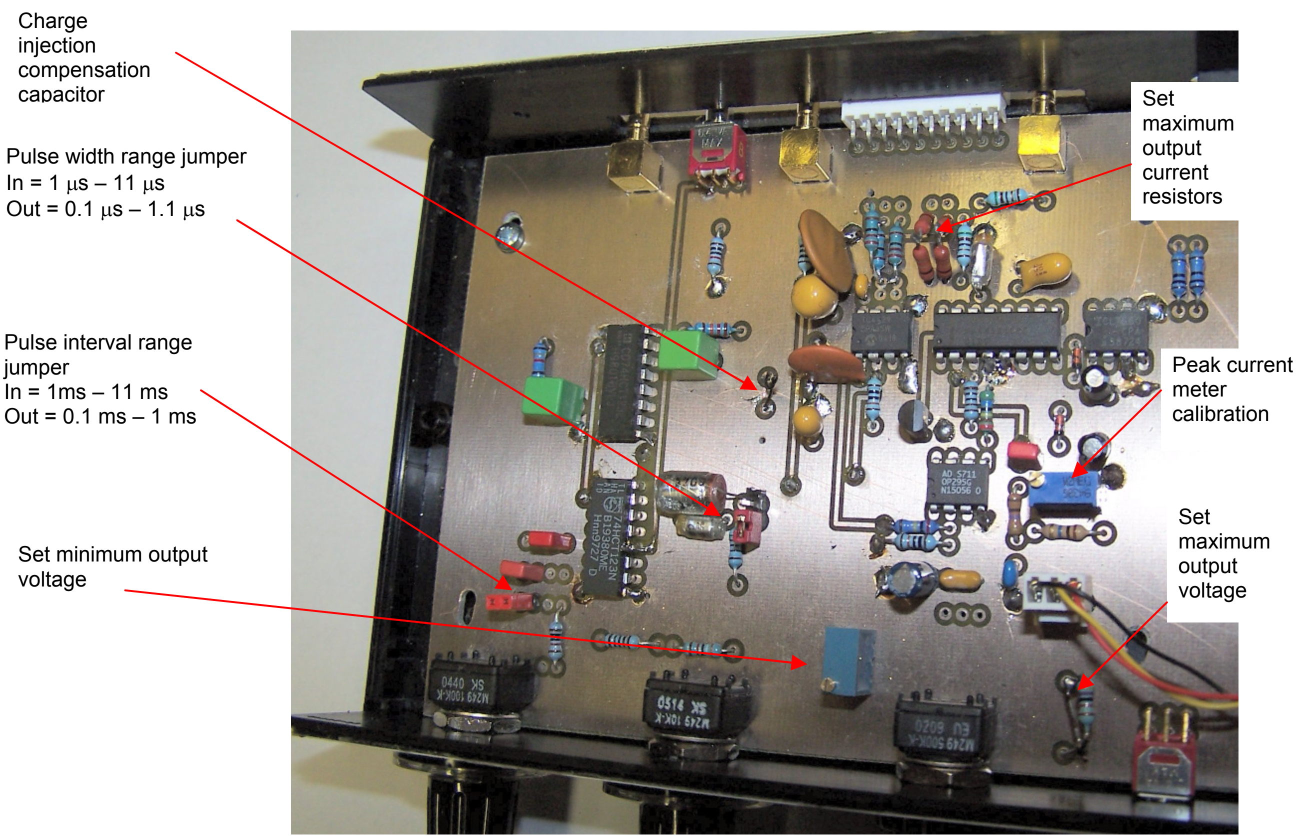
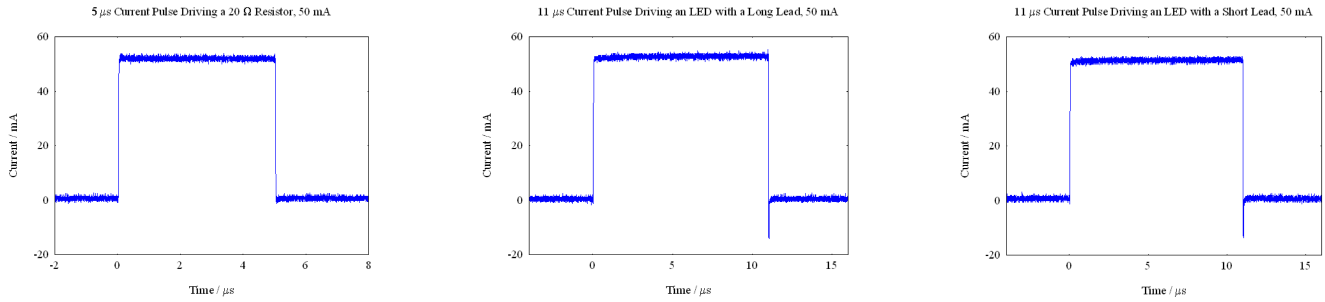


Figure 4: Internal printed circuit board layout.

The performance of the unit is shown in the oscilloscope traces below.

(1) LED driver:



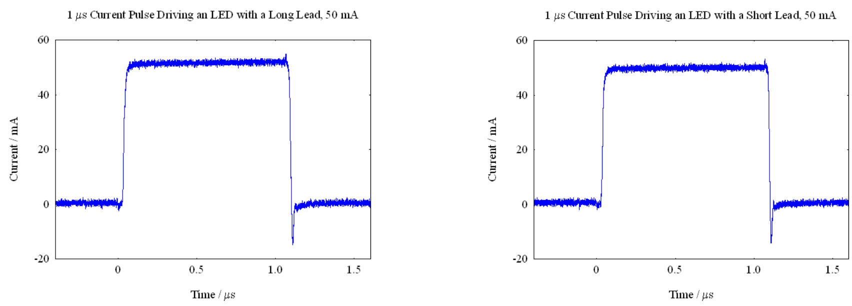


Figure 5: Typical LED driver output waveforms, (50 mA peak output current) into a resistive load (5 µs pulse width, above), into the super-luminescent LED (11 µs pulse width, top, 1 µs pulse width, bottom), connected through long cables (800 mm, middle panels) and short cables (<30 mm, far right panels).

(2) Laser driver

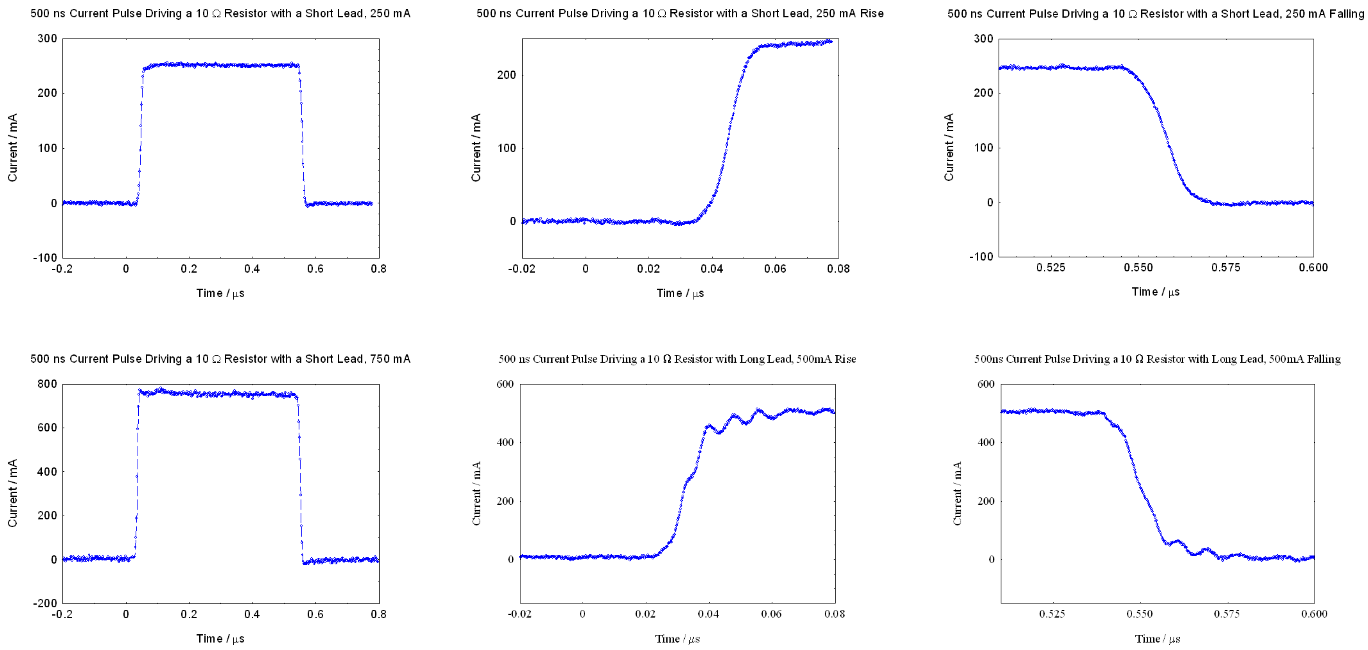


Figure 6: Typical output waveforms of the laser driver, driving a 10 Ω resistive load through short and long output cables, obtained with a 300 MHz bandwidth oscilloscope. The LED driver output waveforms are not substantially different and show the same trends.

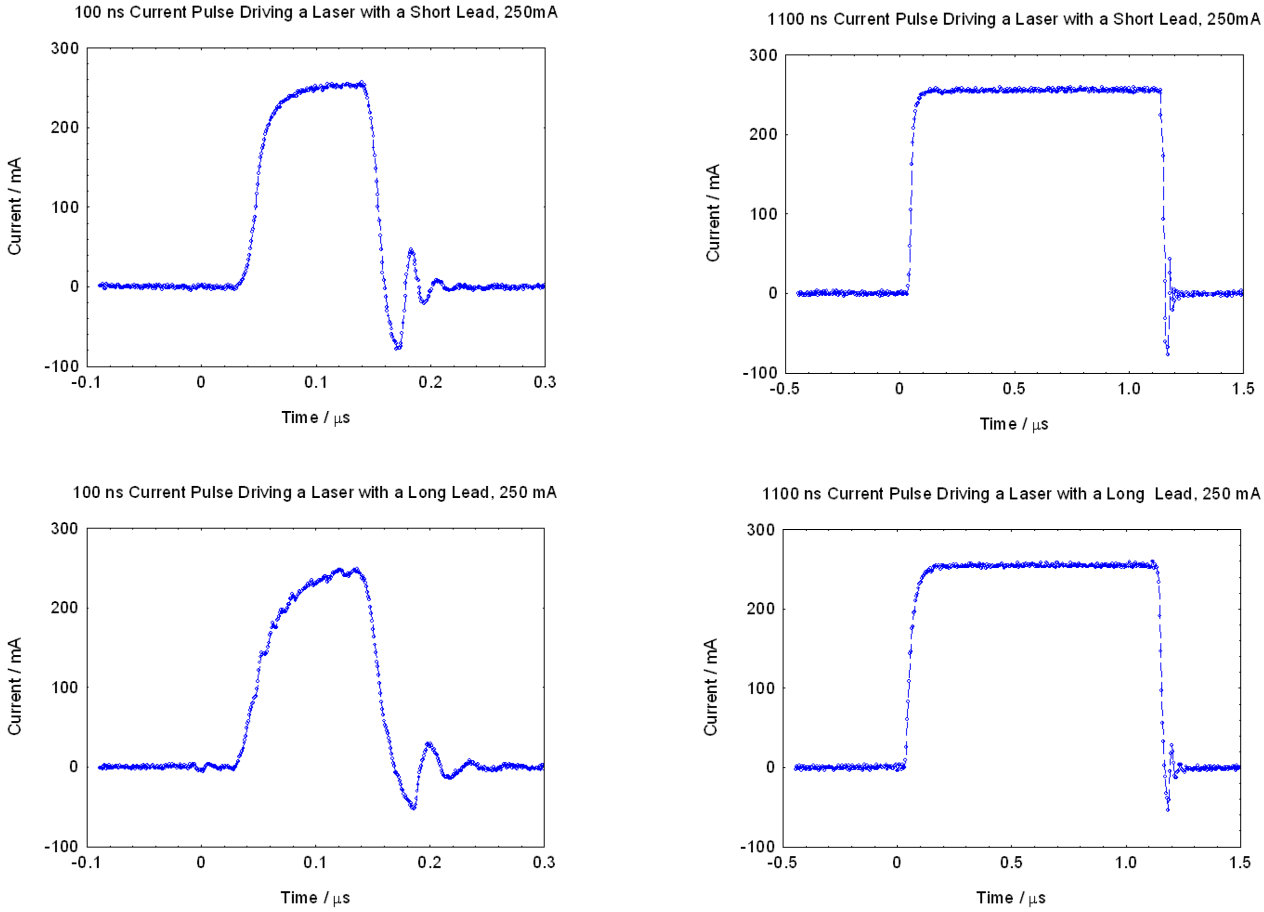


Figure 7: Typical output waveforms, (250 mA peak output current) into a laser emitter at operating at 100 ns and 1 µs pulse widths connected through short (<30 mm) and long (800 mm) cables.

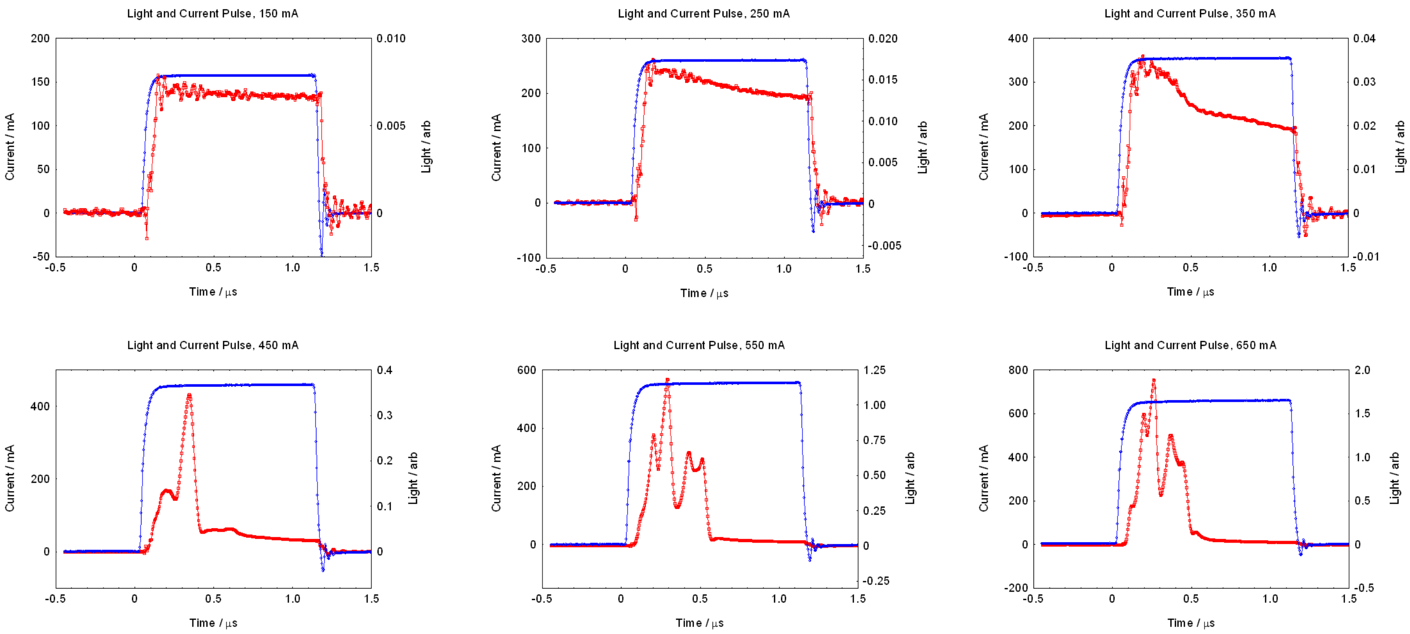


Figure 8: Comparison of output current waveforms and optical outputs for one of the laser emitters. The optical output waveforms are detected with a variable gain avalanche photodiode detector, detection bandwidth 40 MHz. The optical outputs are on an arbitrary sensitivity scale and represent relative output and to indicate pulse shape. Electrical (blue) and optical (red) waveforms are shown.

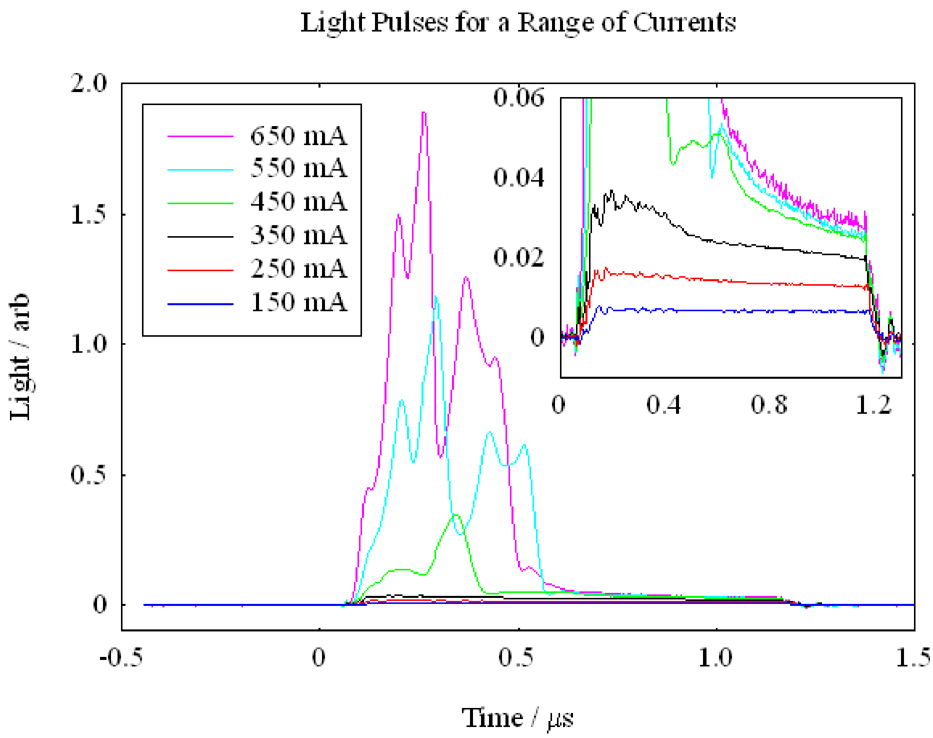


Figure 8: Optical outputs from Figure 8 plotted on 'common' sensitivity scales, showing increased outputs above some 400 mA for this particular emitter. Note that pulse widths above around 500 ns are not effective in producing increased optical output.

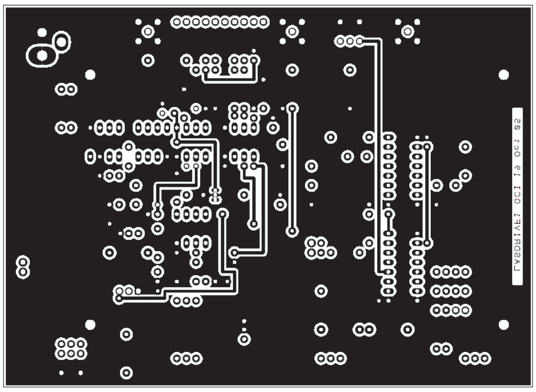
Do's and Don'ts

- Do not leave the unit on when not in use, as the quiescent operating current will eventually drain the battery.
- Do not rely too much on the pulse width and pulse interval calibrations on the front panel dials: knobs can all too easily slip and in any case the tolerance and linearity of potentiometers is relatively poor such that calibration throughout the time ranges cannot be relied up.
- Do not worry about changing the maximum output voltage setting resistor within the unit, refer to the circuit for actual value (typically up to 1 MΩ).
- Do not short the output connections to earth (i.e. the 'outers' of the coaxial connectors) and do not apply external signals to these connections. Although no damage to the unit will result from a short to ground, if the negative connection is thus shorted, the current sensing resistor is then not in circuit and an incorrect current reading will be obtained.
- Do not apply voltages greater than +5V or less than 0V, relative to system ground, on any connectors other than the DC power supply input.
- Do not apply more than +9V to the DC supply connector and use only the AC adaptor supplied (regulated +9V).
- Do not terminate the current monitor output with anything other than a high impedance oscilloscope input, connected through a short cable.
- Do use the unit with an oscilloscope whenever possible, this will add confidence to the correct operation and pulse widths/intervals/currents can be easily checked.
- Do remember that the unit's panels are home-made; this has the disadvantage that they are probably easily scratched, but the distinct advantage that they can be easily replaced!
- Do turn down the pulse amplitude knob to minimum just before switching off; this will not only leave the unit 'ready' for safe turn-on but will also prevent inevitable switch bounce from producing unexpected spikes at the output.
- Do monitor the optical output from the emitter driven by the unit, whenever possible.

PULSED LASER DRIVER SUPPLY #1 COMPONENT LIST – BIOCHIPS PROJECT

ITEM	SOURCE	DESCRIPTION	#	PART #	SUPPLIER	EACH	TOTAL
PRINTED CCT. BOARD		IN-HOUSE	1 OFF	LASDRIVF1.pcb	GCI	£ 20	£ 20
POWER SUPPLY REGULATED 9V 250 mA 2.2W	MASCOT	9583 000045	1 OFF	400-6692	RS COMPS	£ 8.43	£ 8.43
CASE Black 205 x 108 x 38 mm	PACITEC	71902-510-000	1 OFF	239-7384	RS COMPS	£ 9.79	£ 9.79
BATTERY HOLDER / SINGLE PP3	BULGIN	BX0023	1 OFF	593-704	RS COMPS	£ 2.18	£ 2.18
BATTERY PP3 550 mAhr	DURACELL	PP3 MN1604	1 OFF	249-853	FARNELL	£ 2.36	£ 2.36
DC INPUT CONNECTOR 2.5mm 1A socket	CLIFF	DC10B	1 OFF	224-960	FARNELL	£ 0.44	£ 0.44
SMB R/A CONNECTORS	PROTECH	1252B13GT30G50	3 OFF	16-1508	RAPID	£ 2.05	£ 6.15
3.5 digit METER, 1.999 *LASER MODEL*	LASCAR	EMV1025S-03	1 OFF	200 mV	LASCAR	£18.68	£ 18.68
CONTROL KNOBS	ELMA	020-3520	3 OFF	320-365	FARNELL	£ 1.25	£ 3.75
CONTROL KNOB STATOR	ELMA	043-3220	2 OFF	321-254	FARNELL	£ 0.91	£ 1.82
CONTROL KNOB DIALS 0-11	ELMA	042-3100	2 OFF	321-140	FARNELL	£ 0.81	£ 1.62
CONTROL KNOB INSERT	ELMA	040-3020	2 OFF	320-845	FARNELL	£ 0.21	£ 0.42
NUT, 3/8"	ELMA	046-4000	2 OFF	321-280	FARNELL	£ 0.39	£ 0.78
CONTROL KNOB NUT COVER LINED	ELMA	044-3120	1 OFF	320-778	FARNELL	£ 0.52	£ 0.52
SWITCH, front 2p2w THREADED	ULTRA MIN	2P on-on r/a,	1 OFF	448-1037	RS COMPS	£ 3.20	£ 3.20
SWITCH, rear 1p2w	C & K.	1P on-on r/a, T101MH9ABE	1 OFF	986-070	FARNELL	£ 1.68	£ 1.68
2 PIN LINK/JUMPER	HARWIN	M7571-05	2 OFF	148-029	FARNELL	£ 0.21	£ 0.42
2 PIN HEADER	HARWIN	M20-9990205	2 OFF	512-035	FARNELL	£ 0.094	£ 0.188
2 PIN MOLEX CABLE CONN. POLARISED	MOLEX	22-01-2025	1 OFF	143-126	FARNELL	£ 0.129	£ 0.129
2 PIN HEADER / PINS / POLARISED	MOLEX	22-27-2021	1 OFF	143-139	FARNELL	£ 0.32	£ 0.32
3 PIN MOLEX CABLE CONNECTOR, POLARISED	MOLEX	22-01-2035	1 OFF	143-127	FARNELL	£ 0.141	£ 0.25
3 PIN HEADER / PINS / POLARISED	MOLEX	22-27-2031	1 OFF	143-140	FARNELL	£ 0.36	£ 0.36
10 PIN MOLEX R/A CONNECTOR, POLARISED	MOLEX	22-05-7108	1 OFF	146-697	FARNELL	£ 0.88	£ 0.88
10 PIN MOLEX CABLE CONNECTOR	MOLEX	22-01-2105	1 OFF	143-131	FARNELL	£ 0.26	£ 0.26
OPAMP / DUAL	AD	OP295GP	1 OFF	310-789	RS COMPS	£ 4.10	£ 4.10
REGULATOR	NATIONAL	LM78L05ACZ	1 OFF	648-488	RS COMPS	£ 0.19	£ 0.19
ANALOGUE SWITCH	MAXIM	MAX4591CPE	1 OFF	MAX 4591 CPE	MAXIM	$ 1.68	$ 1.68
OUTPUT DRIVER	TELCOM	TC4429CPA	1 OFF	295-073	FARNELL	£ 2.75	£ 2.75
VOLTAGE DOUBLER	INTERSIL	ICL7660CPA	1 OFF	408-554	FARNELL	£ 0.72	£ 0.72
MONOSTABLE	PHILIPS	74HCT123	2 OFF	381-986	FARNELL	£ 0.39	£ 0.78
DOUBLER DIODES	MULTICOMP	1N4148	2 OFF	956-5124	FARNELL	£ 0.011	£ 0.011
PULSE INTERVAL POTENTIOMETER	SPECTROL	100 K 249-7-10-100K	1 OFF	614-233	FARNELL	£ 2.01	£ 2.01
PULSE WIDTH POTENTIOMETER	SPECTROL	10 K 249-7-10-10K	1 OFF	614-208	FARNELL	£ 2.01	£ 2.01
OUTPUT AMPLITUDE POTENTIOMETER	SPECTROL	500 K 249-7-10-500K	1 OFF	614-245	FARNELL	£ 2.01	£ 2.01
PRESET, CALIBRATION	BOURNS	2 MΩ 3296W-1-205LF	1 OFF	935-3267	FARNELL	£ 1.23	£ 1.23
PRESET, SET MINIMUM CURRENT	BOURNS	100 KΩ 3296W-1-104LF	1 OFF	935-3194	FARNELL	£ 1.23	£ 1.23
RESISTOR, CURRENT SENSE *LASER MODEL*	MULTICOMP	2 Ω MRS25	2 OFF	335-289	FARNELL	£ 0.04	£ 0.08
RESISTOR, CURRENT LIMIT *LASER MODEL*	MULTICOMP	10 Ω PR01	1 OFF	337-614	FARNELL	£ 0.153	£ 0.153
RESISTOR, SENSE O/P *LASER MODEL*	MULTICOMP	51 Ω MRS25	1 OFF	335-629	FARNELL	£ 0.04	£ 0.04
RESISTOR, FAST PEAK CHARGING	MULTICOMP	51 Ω MRS25	1 OFF	335-629	FARNELL	£ 0.04	£ 0.04
RESISTOR, SLOW PEAK CHARGING	MULTICOMP	1 kΩ MRS25	1 OFF	335-940	FARNELL	£ 0.04	£ 0.04
RESISTOR, SERIES METER ATTENUATOR	NEOHM	100 MΩ RGP0207CHJ100M	1 OFF	247-7834	RS COMPS	£ 0.64	£ 0.64
RESISTOR, SHUNT METER ATTENUATOR	MULTICOMP	10 MΩ MRS25	1 OFF	336-907	FARNELL	£ 0.04	£ 0.04
RESISTOR, PEAK HOLD DISCHARGE	MULTICOMP	5.6 MΩ MRS25	1 OFF	336-841	FARNELL	£ 0.04	£ 0.04
RESISTOR, REP RATE SERIES	MULTICOMP	10 KΩ MRS25	1 OFF	336-180	FARNELL	£ 0.04	£ 0.04
RESISTOR, REP RATE SHUNT	MULTICOMP	1 MΩ MRS25	1 OFF	336-660	FARNELL	£ 0.04	£ 0.04
RESISTOR, PULSE WIDTH SERIES	MULTICOMP	510 Ω MRS25	1 OFF	335-861	FARNELL	£ 0.04	£ 0.04
RESISTOR, PULSE WIDTH SHUNT	MULTICOMP	39 kΩ MRS25	1 OFF	336-324	FARNELL	£ 0.04	£ 0.04
RESISTOR, PULSE WIDTH SHUNT, PADDING	MULTICOMP	1 kΩ MRS25	1 OFF	335-940	FARNELL	£ 0.04	£ 0.04
RESISTOR, MAXIMUM AMPLITUDE LIMIT	MULTICOMP	ADJUST ON TEST MRS25	1 OFF	---	FARNELL	£ 0.04	£ 0.04
RESISTOR, SYNC OUT	MULTICOMP	470 Ω MRS25	1 OFF	335-850	FARNELL	£ 0.04	£ 0.04
RESISTOR, SYNC IN	MULTICOMP	10 kΩ MRS25	1 OFF	336-180	FARNELL	£ 0.04	£ 0.04
RESISTOR, DELAY	MULTICOMP	12 kΩ MRS25	1 OFF	336-131	FARNELL	£ 0.04	£ 0.04
RESISTOR, DELAYED PULSE	MULTICOMP	1.8 kΩ MRS25	1 OFF	336-002	FARNELL	£ 0.04	£ 0.04
RESISTOR, DRIVER PULL-UP	MULTICOMP	100 KΩ MRS25	1 OFF	336-427	FARNELL	£ 0.04	£ 0.04
RESISTOR, OPAMP FEEDBACK	MULTICOMP	200 KΩ MRS25	1 OFF	336-490	FARNELL	£ 0.04	£ 0.04
RESISTOR, OPAMP GAIN	MULTICOMP	100 KΩ MRS25	1 OFF	336-427	FARNELL	£ 0.04	£ 0.04
RESISTOR, OFF LOAD SHORT CIRCUIT #1	MULTICOMP	10 Ω MRS25	1 OFF	335-459	FARNELL	£ 0.04	£ 0.04
RESISTOR, OFF LOAD SHORT CIRCUIT #2	MULTICOMP	10 Ω MRS25	1 OFF	335-459	FARNELL	£ 0.04	£ 0.04
CAPACITOR, REP RATE, SLOW	WIMA	220 nF MKS02	1 OFF	106-115	FARNELL	£ 0.37	£ 0.37
CAPACITOR, REP RATE, SLOW, PADDING	WIMA	6.8 nF MKS02	1 OFF	149-105	FARNELL	£ 0.181	£ 0.181
CAPACITOR, REP RATE, FAST	WIMA	22 nF MKS02	1 OFF	149-108	FARNELL	£ 0.21	£ 0.21
CAPACITOR, PULSE WIDTH, SLOW	LCR COMPS	2.2 nF polystyrene	1 OFF	105-889	FARNELL	£ 1.03	£ 1.03
CAPACITOR, PULSE WIDTH, FAST	LCR COMPS	180 pF polystyrene	1 OFF	303-9924	FARNELL	£ 0.70	£ 0.70
CAPACITOR, DELAY	WIMA	10 nF FKP2	1 OFF	143-703	FARNELL	£ 0.29	£ 0.29
CAPACITOR, DELAYED PULSE	WIMA	10 nF FKP2	1 OFF	143-703	FARNELL	£ 0.29	£ 0.29
CAPACITOR, AMPLITUDE DECOUPLE	VISHAY BC	100 nF 2252325 00104	1 OFF	354-9641	FARNELL	£ 0.30	£ 0.30
CAPACITOR, LOGIC DECOUPLE	VISHAY BC	100 nF 2252325 00104	1 OFF	354-9641	FARNELL	£ 0.30	£ 0.30
CAPACITOR, REGULATOR INPUT	MULTICOMP	10 µF CB1E106M2ICB	1 OFF	416-4374	FARNELL	£ 0.30	£ 0.30
CAPACITOR, REGULATOR OUPUT	MULTICOMP	10 µF CB1E106M2ICB	1 OFF	416-4374	FARNELL	£ 0.30	£ 0.30
CAPACITOR, VOLTAGE DOUBLER 1	RUBYCON	10 µF 50MS510M6357	1 OFF	105-867	FARNELL	£ 0.158	£ 0.158
CAPACITOR, VOLTAGE DOUBLER 2	RUBYCON	10 µF 50MS510M6357	1 OFF	105-867	FARNELL	£ 0.158	£ 0.158
CAPACITOR, DRIVER DECOUPLING 1	MULTICOMP	10 nF MCFYU5103Z5	1 OFF	941-1852	FARNELL	£ 0.051	£ 0.051
CAPACITOR, DRIVER DECOUPLING 2	VISHAY	100 nF BC 2252 325 00104	1 OFF	354-9641	FARNELL	£ 0.30	£ 0.30
CAPACITOR, DRIVER DECOUPLING 3	MULTICOMP	47 µF CB1V476M2NCB	1 OFF	416-4544	FARNELL	£ 2.36	£ 2.36
CAPACITOR, DRIVER DECOUPLING 4	ELNA	100 µF RE3-25V101M	1 OFF	361-8535	FARNELL	£ 0.66	£ 0.66
CAPACITOR, FAST INTEGRATOR	LCR COMPS	330 pF FSC	1 OFF	105-063	FARNELL	£ 1.03	£ 1.03
CAPACITOR, FAST INTEGRATOR TRIM	n/a	1-2 pF	1 OFF	Wire twist	n/a	n/a	n/a
CAPACITOR, SLOW INTEGRATOR	WIMA	47 nF MKS02	1 OFF	149-110	FARNELL	£ 0.22	£ 0.22
CAPACITOR, METER DRIVE	VISHAY	10 nF BC 2252 325 00103	1 OFF	354-9616	FARNELL	£ 0.156	£ 0.156
TOTAL							**≈ £ 120**

The top and bottom printed circuit board layouts are shown in Figure 9 below:



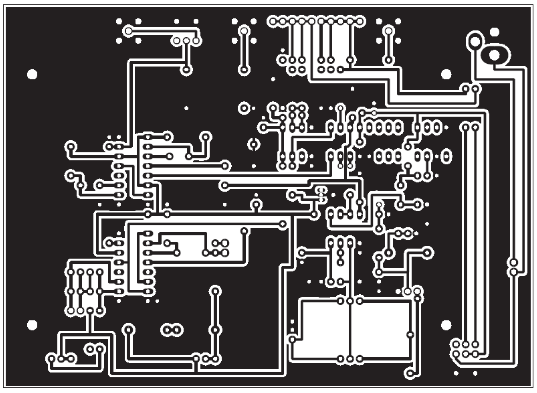


Figure 9: The upper, component (left) and lower track (right) printed circuit board layouts, scale 2:1.

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