High-voltage Probe

Home made and differential, too

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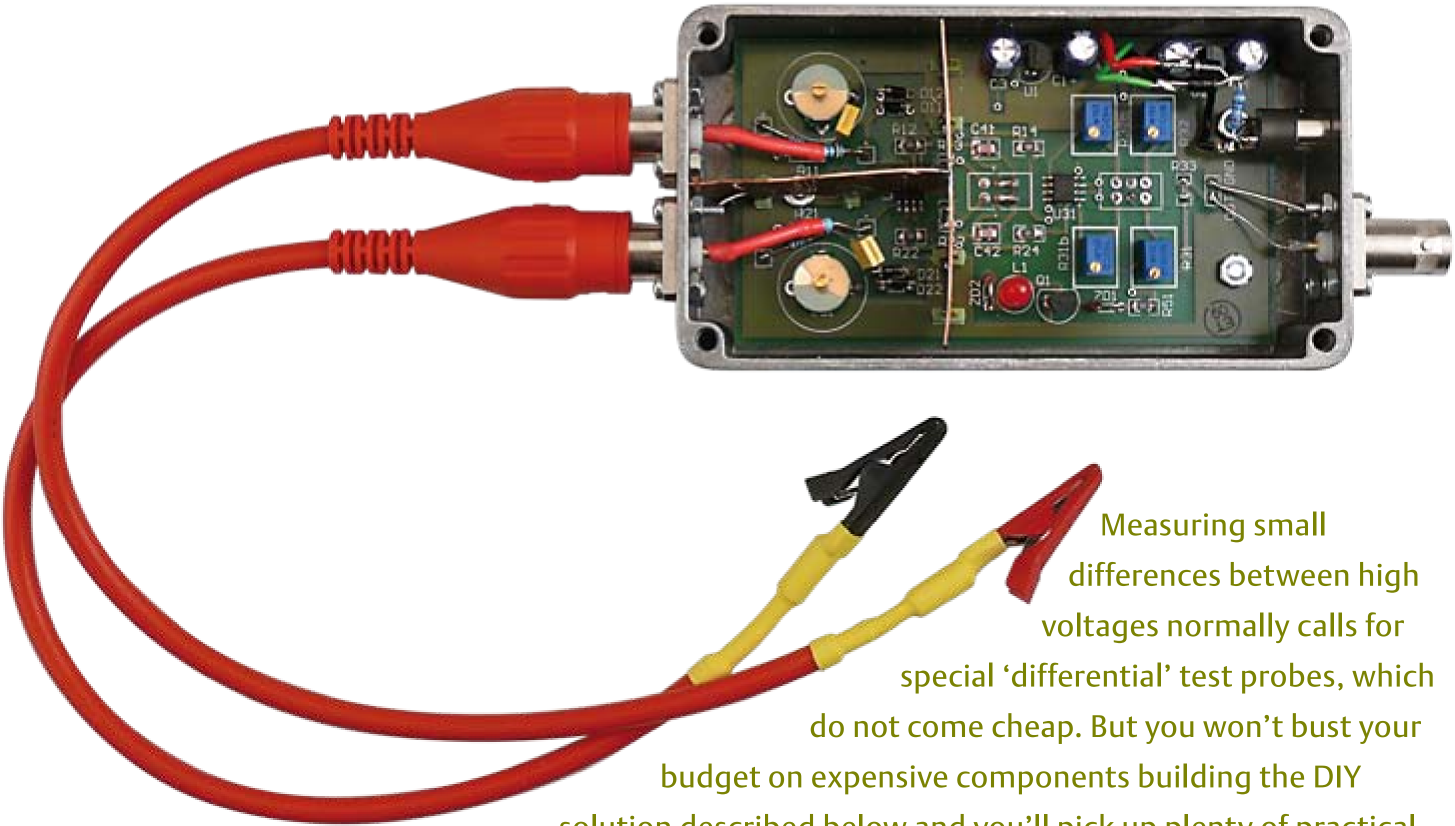

Measuring small differences between high voltages normally calls for special 'differential' test probes, which do not come cheap. But you won't bust your budget on expensive components building the DIY solution described below and you'll pick up plenty of practical know-how in the process.

Many circuits employ high voltages. The two best-known examples are switch-mode power supplies and vacuum tube circuitry. A relatively new application is found in hybrid and electric automobiles, which operate with high battery voltages (and dangerously high currents) in order to reduce voltage drop and the cross-sectional diameter of cabling.

Whilst any decent multimeter is adequate for measuring high voltages, it's not so handy for measuring small fluctuations in high DC or AC voltages overlaid on these. Frequently, moreover, we are not interested so much in the absolute value of a high voltage as much as in the difference between two separate high-voltage levels, such as (for example) the differing anode voltages of a push-pull amplifier or at switching nodes in a phase shift full-bridge topology transformer (within high output level switch-mode power supplies).

Starting point

One solution would be to use two standard high-voltage test probes (not too expensive, with serviceable characteristics) together with a digital oscilloscope so as to calculate the signal difference using mathematical functions. This method has three disadvantages:

1. This means using two channels of the oscilloscope, which makes it harder to observe several signals simultaneously.
2. Both signals are digitised at the resolution of the oscilloscope (generally 8 bits maximum), so that errors add up. Subtracting two large, almost identical voltage values is always problematic, increasing the risk of measurement errors.
3. Since the timing correlation between the two measurement channels is related to factors such as cabling and earth (ground) loops and mathematical functions within the oscilloscopes can throw up random and deterministic fluctuations, the timing information of the signal is not very trustworthy, particularly at higher signal frequencies.

Remedy can be found in the so-called 'high-voltage differential test probe'. This is a probe set enhanced with a differential amplifier able to accept very high voltages on its inputs and amplify only the voltage difference between the two input connections, whilst at the same time suppressing common-mode signals (signals of exactly the same level on each input).

It might sound as if a simple differential amplifier with voltage dividers on its inputs could do this job but life is seldom this simple. For proof just see how expensive commercial differential test probes are for this kind of measurement task. A good example is the Tektronix P5200. On the Tek website [1] you'll find an extremely readable application note [2] on using high-voltage probes. The maximum input voltage differential is given in the data sheet as ±1300 V and the bandwidth as 25 MHz. Digging deeper into the data, a value of particular interest is the CMRR or Common-Mode Rejection Ratio, which is the ability of a differential amplifier to reject the portion of the signal common to both the + and – inputs. The impressive value of 80 dB at 60 Hz drops off rapidly at higher frequencies, for instance to 50 dB at 100 kHz, which is pretty good nevertheless. A small differential signal becomes progressively more difficult to measure as the frequency of the common-mode signal rises. A frequency sweep of the common-mode signal will indicate that the output signal increases with the frequency of the common-mode signal but this is an illusion. At higher frequencies a greater part of the common-mode signal reaches the output by means of (parasitic) capacitive coupling, making it very difficult to improve the CMRR for high frequencies.

Test probes and oscilloscopes

Although the oscilloscope is a very handy instrument for taking measurements, it can easily lead you astray when you misinterpret what's indicated on the display. A whole load of measurement errors can also occur, so using a differential test probe means keeping your wits about you.

The specification of our low cost, easy-to-build differential test probe is shown in the panel 'Characteristics'. The switchable attenuation feature is a boon when the differential signal being measured is small and the common-mode signal is very large. Here we need to ensure that the test probe remains operating linearly and is not overdriven. An overload indicator of the kind provided with commercial differential test probes was omitted for reasons of simplicity.

Bandwidth limitation is important for measurements with spurious high-frequency signals, as in switch-mode power supplies. The frequency sweeps are shown in **Figure 1**. The upper of the two curves indicates the output signal at –20 dB attenuation both with (in orange) and without (in green) bandwidth limiting. The blue line is the –40 dB setting with the 500 kHz filter switched in. As expected, the frequency response is very linear, with a maximum cut-off frequency of approx. 1 MHz. The red line shows the common-mode output signal relative to the frequency. By calculation this gives a CMRR of about 55 dB at low frequencies, which falls to about 35 dB at higher frequencies. This fall-off starts at around 6 kHz and is caused mainly by parasitic coupling inside the test probe. It is further influenced at higher frequencies by parasitic coupling within the op-amp.

The maximum input voltage of about ±1000 V was soak-tested in the lab with constant voltage over an extended period. BNC connectors and suitable HV cables are specified for these tests. The input impedance of the circuit must likewise be laid out for high voltages. The resistors used (R1 in **Figure 3**) should be rated for 1600 V (standard resistors are usable up to only 250 V). Alternatively you can wire several resistors of lower voltage rating in series to divide the voltage (assuming all of these resistors have the same value).

One more tip concerning the measurement cables: the cabling on the two differential inputs should be as far identical as possible, since any disparity will unbalance the setup and cause measurement errors. For our prototype we cut a short coaxial test lead with BNC connectors into two halves of equal length, with insulated croc clips fixed to the free ends and the transition insulated with heatshrink tubing (see **Figure 2**). Because these cables represent a capacitive load to the measurement setup, they need to be as short as practically possible.

Characteristics

- Differential attenuation switchable in two stages (–20 dB/–40 dB)
- Bandwidth 1 MHz, switchable limit at 500 kHz
- Maximum input voltage ±1000 V (peak value)
- Maximum output voltage ±10 V (at min. terminating impedance 1 kΩ)
- Common-mode suppression 55 dB at 6 kHz, 35 dB at 600 kHz

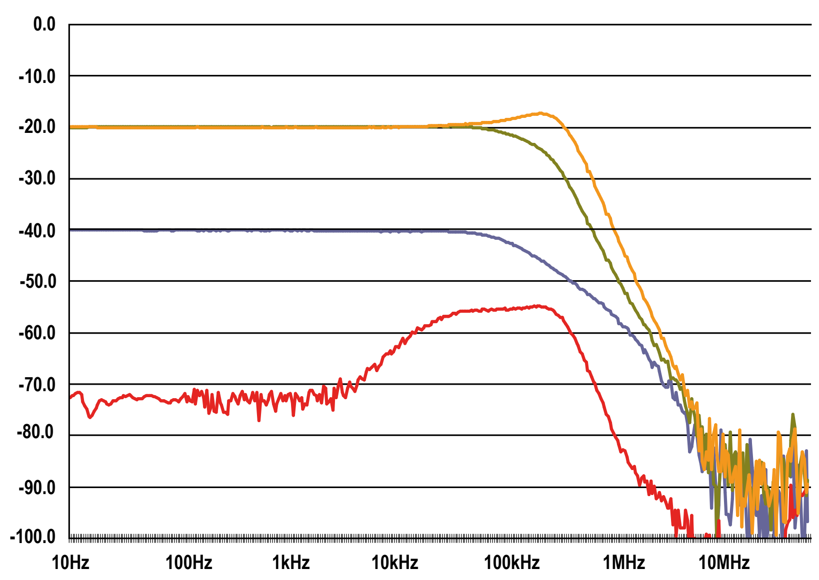

Figure 1. Frequency response at both amplification settings, each with and without the 500 kHz filter. The lower curve indicates the common mode suppression.

Figure 2. Measurement cable with fully insulated croc clips.

Caution: lethal voltages!

Handling high voltages demands setting up properly, proceeding with caution and taking all necessary safety precautions — even if you're in a rush and it seems too much of a hassle. Your life is worth more than rapid results. Before testing a circuit with the type of high-voltage test probe shown here make sure you are familiar with the safety regulations. For devices operating at voltages above 50 VAC or 120 VDC testing live circuitry is allowed only if there are valid reasons why the power cannot be turned off (such as for taking voltage measurements). Under German law these operations may only be carried out by qualified electrical technicians, not by trainees and apprentices.

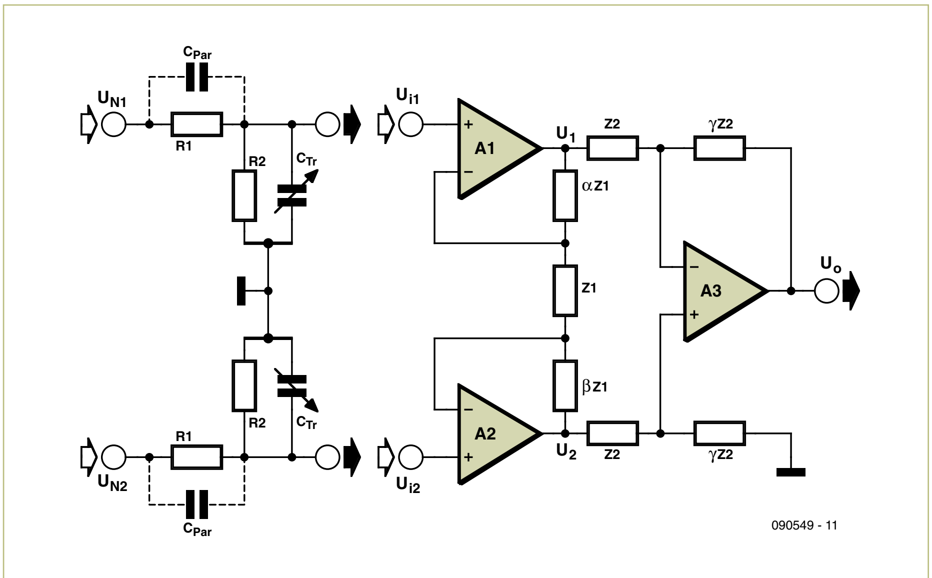

Figure 3. Block diagram with input attenuator (left) and instrumentation amplifier (right).

Input voltage division ratio: $DR_{1,2} = \frac{R_2}{R_1 + R_2}$

Output voltage (first opamp): $U_1 = (1 + \alpha + \beta) \times U_{in1} \times DR_1$

Output voltage (second opamp): $U_2 = (1 + \alpha + \beta) \times U_{in2} \times DR_2$

Output voltage (test probe): $U_{out} = (U_1 - U_2) \times \gamma$

Circuitry and input design

The circuit (**Figure 3**) is basically a differential amplifier using three op-amps, sometimes described in the literature as instrumentation amplifiers. A1 and A2 act as high-impedance inputs and amplify differentially, whilst A3 is an actual (classic) differential amplifier. Our circuit offers an interesting advantage over the classic differential amplifier, however: whilst the CMRR in a simple differential amplifier depends on the matching of the resistors Z2, it is here greater by the factor

$\gamma \times (1 + \alpha + \beta)$

This, however, creates amplification and consequently the danger of overload when a large common-mode signal is present. For this reason we must configure the amplification and input voltage divider to produce maximum CMRR in the linear operating range of the op-amp. In the circuit we selected 1 for the value of α and ß, whilst α in the two attenuator stages is 0.657 (at –40 dB) and 6.57 (at –20 dB). Z1 and Z2 are set relatively low at 1 kΩ but with the advantage that the influence of parasitic capacitance in the circuit is reduced.

The formulae for calculating the values are set out in the panel 'Formulae for Figure 3'. In your calculations ensure that the op-amp output voltages remain in the range ±12 V.

R1 and R2 form the input voltage divider. R1 must have high resistance for a high input voltage range and low loading on the signal under measurement. Because the parasitic capacitance C_{par} reduces the division ratio at high frequencies, a trimmer capacitor is fitted in parallel to R2 for compensation. We selected 10 MΩ for R1 and 51 kΩ for R2, allowing a 5-30 pF trimmer to provide compensation. The division ratio is around 198. Alignment of the trimmers is the same procedure as for other test probes, applying a square-wave signal and obtaining the optimum curve shape. Many oscilloscopes have a square-wave generator built-in for this purpose.

Construction

Figure 4 shows the construction of the input stage. The two input resistors (for minimising leakage currents) should be insulated with heatshrink tubing. Additional ceramic capacitors are wired in parallel with the two trim-caps, to extend the compensation range.

The complete circuit (apart from the two 10 MΩ input resistors) is shown in **Figure 5**. On the left-hand side the two extra ceramic capacitors can be seen in parallel with the trimmers, also the second divider resistor. The diodes at the inputs (D11/12 and D21/22) are for over-voltage protection; they operate much faster than Zener diodes and their capacity is far lower. The high input resistors (10 MΩ) reliably clip any over-voltages from the diodes plus any current leakage from the power supply. For good frequency response it is vital to minimise parasitic capacitance at nodes in the layout.

The differential amplifier formed by U31A follows after the amplifiers U11A and U11B with their negative feedback resistors. To achieve the best match between amplification and CMRR, the negative feedback resistors for U31A take the form of precision trimpots. The output is terminated with a 50 Ω resistor.

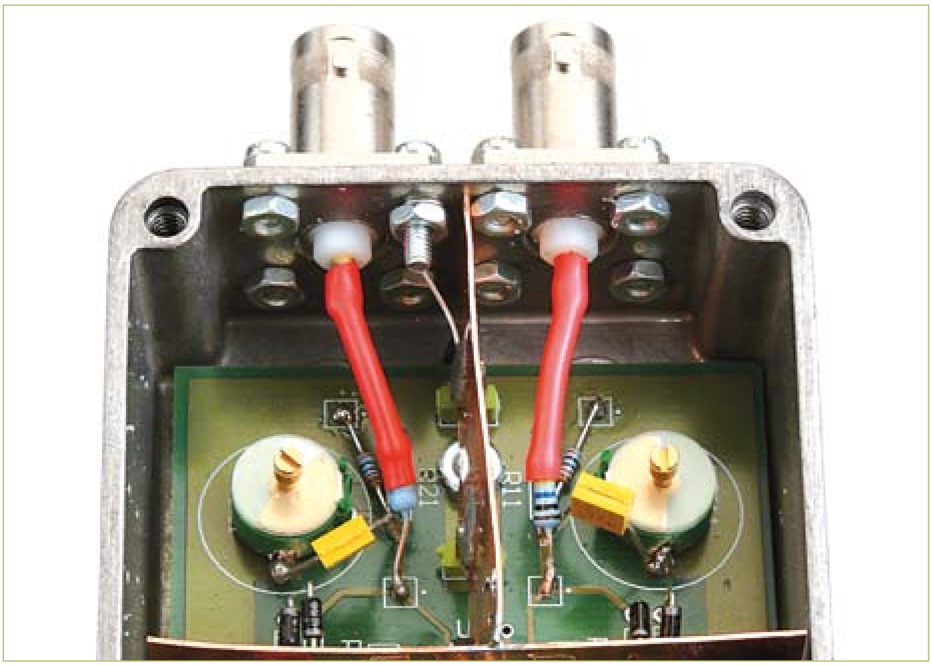

Figure 4. Constructing the input stage.

Switch S1 enables the amplification factor and the attenuation of the test probe to be toggled. S2 switches the bandwidth limiting using a 330 pF capacitor in parallel with the negative feedback resistors in the first stage.

The only special feature of the power supply using voltage regulators U1 and U2 is the little module using Q1 and LED L1 for monitoring the two voltages. Close to the

Calibration

Calibration is carried out as follows:

1. Connect power supply, observe red LED is lit. Check operating voltages (±15 V) and op-amp output voltages (a few mV).

2. Connect oscilloscope to the output (output terminated in 50 Ω).

3. Set R31 and R31b in the middle of their range and connect a 1-kHz square-wave signal with an amplitude of around 10 V_{pp} to one of the two inputs – the exact value is not so important.

The square-wave signal should be visible on the oscilloscope. Adjust the trimmer capacitor on the relevant input for best square-wave curve shape. The best method is to apply the square-wave signal to trigger the second channel of the oscilloscope and use this for comparison. If the adjustment range is too small you can connect some more small ceramic capacitors in parallel with the trimmer capacitor. If the trimmer capacitor is too large and the input voltage divider behaves like a low-pass filter, you can give the voltage divider a lower impedance (e.g. using 3.3 MΩ for R1 and 16 kΩ for R2). If you find it impossible to achieve a proper square-wave signal you will need to change the physical construction (the parasitic capacity is too large).

4. Adjust the second input in the same way (square-wave signal on this input only).

5. Now adjust R31 and R31b so that the output voltage corresponds exactly to the input voltage attenuated by the factor you have set. For an input signal of 10 V_{pp} the output signal should be exactly 1.0 V_{pp} with S1 set for –20 dB and 100 mV_{pp} in the –40 dB setting.

6. Now apply the same signal to both inputs and adjust R32 and R32b to make the output signal as small as possible (the smaller the better).

7. Repeat steps 5 and 6 several times, as they are mutually interactive. Take care to achieve maximum common-mode suppression with R32/R32b — this is more important than producing the precise attenuation preset by R31 and R31b.

It is important to complete steps 3 and 4 accurately before proceeding with the remaining alignment. Without good frequency response at the input voltage divider stage all the following steps are meaningless. Signal measurement first on one and then on both inputs should be carried out repeatedly at various frequencies from DC to HF. This will also give you a good understanding of how the test probe behaves with differing signals.

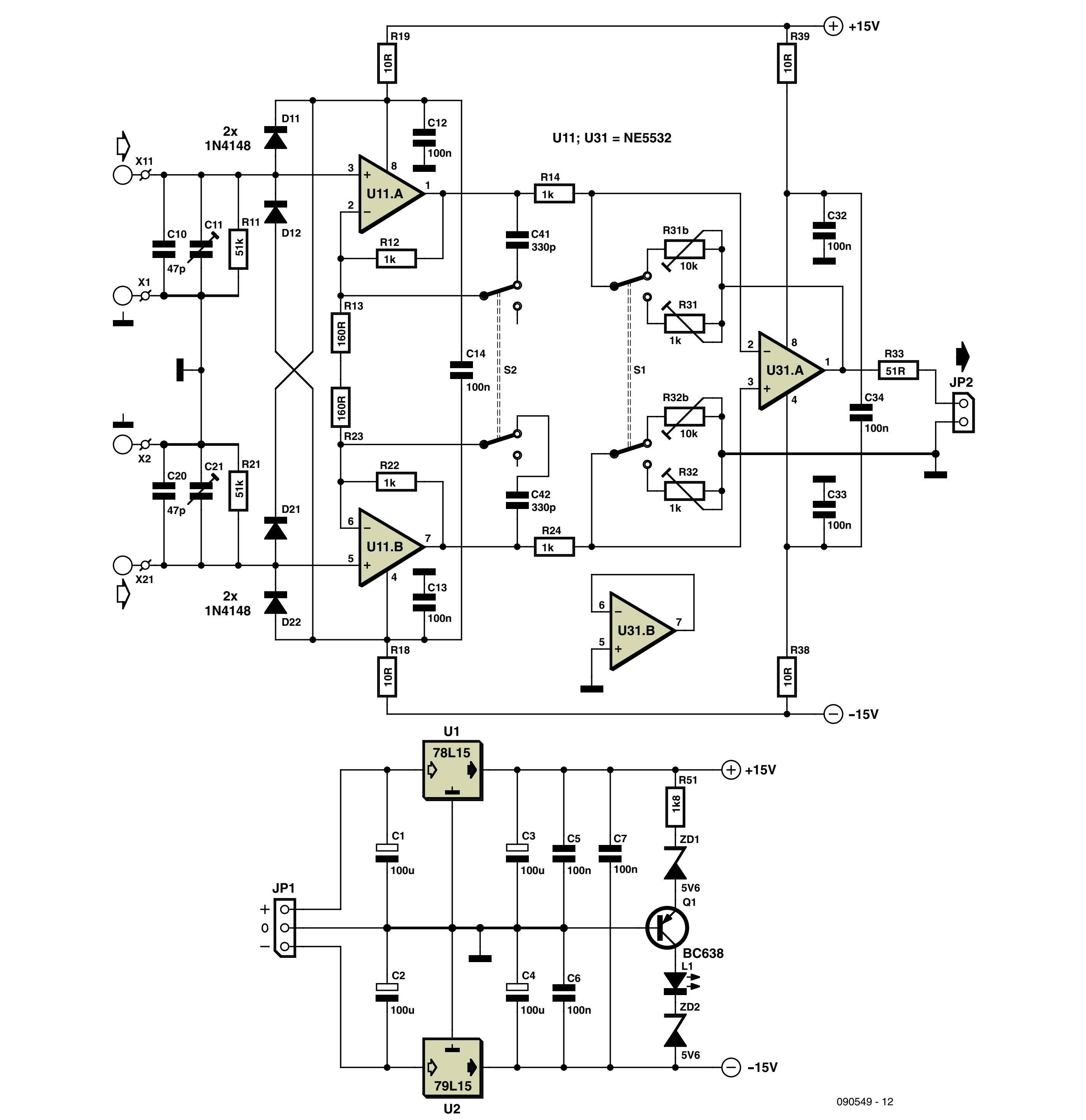

Figure 5. Full circuit (omitting the two 10 MΩ input resistors).

op-amps the voltages are decoupled once more using 10 Ω and 100 nF.

The PCB layout can be downloaded from the Elektor website, where you will also find the component list.

Figure 6 shows how the circuitry is constructed on a PCB built into a diecast aluminium box. The input stage (left) has copper foil laid below it and shielded from the main differential amplifier on the right, so as to minimise capacitive coupling. The copper strips are soldered to the PCB using earthing (grounding) pins. Take care around the inputs to provide adequate insulation and space between the high voltage conductors. For this reason the 10 MΩ input resistors and their connecting leads should be made safe with heat-shrink tubing.

The two switches are mounted on the underside of the PCB and are operated from the lower side of the case housing. At the upper right-hand corner of the PCB are the power supply components and on the right the BNC output socket and power supply connector (around ±18 to ±20 V).

Parasitic capacitance and inductance are

Figure 6. Completed circuitry with the printed circuit board inside the diecast aluminium box.

minimised by the use of surface mount (SMD) resistors and capacitors. The disadvantage of the wider tolerances is offset by precise adjustment of the trimmers. Our lab sample, using 5 % tolerance components, was successfully aligned to a CMRR of more than 60 dB at low frequencies, which corresponds to a resistor tolerance of below 0.1 %.

Applications and options

Commissioning and calibration are explained step by step in the panel 'Calibration'. Remember constantly when taking measurements that high voltages are lethal! Before altering or touching anything on the test bench, switch off the volts and make sure everything is completely dead (capacitors can retain their charge for a long time!). Always work using one hand alone (keep the other one in your trouser pocket!).
The high input impedance simplifies use of the test probe and minimises signal loading at the point of measurement. Signal level readings taken from the oscilloscope display should always take into account the attenuation level selected (–20 or –40 dB). The selected bandwidth (0.5 or 1 MHz) determines the extent to which high frequency oscillations will be visible on the oscilloscope. The input capacity of the test probe is certainly small but can nevertheless, like any capacity, lead to signal degradation or even oscillation at particularly critical points in a circuit.
Should the signal under measurement appear to be flattened or smoothed off above and below, you need to check whether the test probe is still operating linearly or is already being overdriven, because the attenuation is inadequate and/or the input signal is too large. Meaningful measurement is impossible with overloading.
The effective range of the differential test probe can be adjusted by altering the division ratio, for instance to ±100 V for lower voltages. For higher voltages the mechanical design must be changed and the insulation improved (e.g. voltage rating of the input connectors).

With a capacitor in series with R14 and R24 the DC component of the signal is removed entirely, which would enable greater amplification for measuring small signals overlaid on high DC voltages. Capacitors at this stage influence the CMRR very little.
You can also add capacitors between the input divider node points and the op-amp inputs but then you will need an additional resistor to ground at the op-amp input for the bias current, which increases the outlay and worsens the CMRR. A capacitor in series with the 10 MΩ input resistor must possess adequate high-voltage rating, which means bulky form factor and large inductance.

Overall this differential test probe is straightforward to construct and produces a cost-effective alternative to expensive commercial products that will serve you well at frequencies up to 1 MHz. The test probe finds regular use in the author's lab and is particularly useful for audio applications.

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[1] www.tek.com

[2] www2.tek.com/cmswpt/tidetails.lotr?ct=TI&cs=apn&ci=2343&lc=EN

The author

Alfred Hesener is a chartered engineer employed by Fairchild Semiconductor as Application and Marketing Director for the European market.