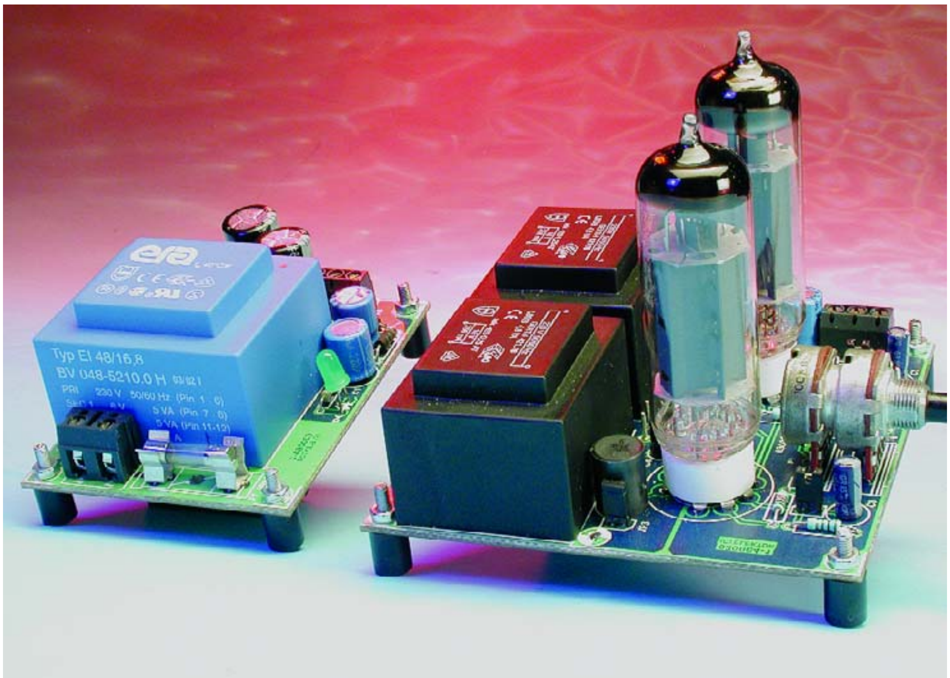
Valve Headphone Amplifier

EL84 (6BQ5) at an anode voltage of 40 V

Design by B. Kainka

It is not just power amplifiers that can deliver the much sought-after warmth of the 'valve sound' — headphone amplifiers can too. What is special about this project is that it is achieved using a safe anode voltage of just 40 V.



Heated debates rage over whether, and how, a valve amplifier sounds different from (or perhaps better than) a modern semiconductor amplifier. There certainly are reasons why a valve amplifier might sound different. First there is the particular form of the characteristic curve (I_a plotted against U_g), whose gentle curve inevitably gives rise to increased distortion as the drive level is increased, especially when negative feedback is not employed. A modern semiconductor amplifier, on the other hand, almost always uses plenty of negative feedback in order to keep distortion to a minimum. However, the human ear itself is non-linear at higher sound levels, and so the 'natural' distortions of a valve can give the impression of a higher volume. Also, a transistor output stage suddenly produces extreme levels of distortion when overdriven, whereas a valve output stage clips more gently.

A second, decisive, factor is the extremely high internal impedance of a valve. The connected audio transducer is therefore practically undamped, whereas in the case of an extremely low-impedance transistor output stage all the self-resonances of a loudspeaker or headphones are strongly damped. This gives a flatter frequency response but simultaneously suppresses the particular character of the audio transducer. This is one of the reasons why the sound of older valve equipment is so often found preferable. At the same time it is also behind a technical problem encountered in the design of valve amplifiers, since a transformer is often required to match the low impedance of the audio transducer.

As mentioned in the article in the September 2003 issue of *Elektor Electronics*, the most important feature of this headphone amplifier is its safety, since it operates with a low anode voltage. The amplifier requires a line-level input of 1 V peak-to-peak and provides plenty of output power.

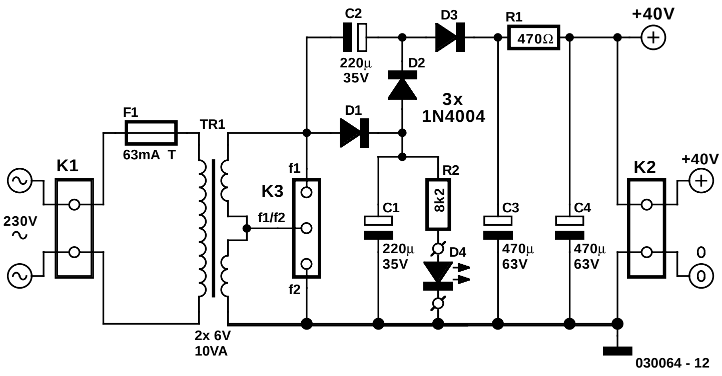


Figure 1. A simple power supply.

EL84 in strange surroundings

The EL84 (or its US equivalent the 6BQ5), a 5 W power output valve usually found in radios, might seem a surprising choice here. Does it really make sense to operate this valve from just 40 V instead of the 250 V suggested in the data sheet? It does: the anode voltage of 40 V is safe and entirely adequate for our purposes here. We do get a lower transconductance and a considerably lower anode current (of around 5 mA), but this does not do any harm to the valve. The anode power dissipation will thus be some 200 mW, and so there should be more than enough output power for driving headphones.

The EL84/6BQ5 is also relatively inexpensive and readily available: it is still in production, as it is still used in many medium power hi-fi amplifiers. Of course, an EL34 or an EL504 could also be used, although these devices are respectively more expensive and harder to obtain.

A further reason for choosing the EL84/6BQ5 is that it makes constructing the power supply more straightforward. The valve requires a heater voltage of 6.3 V and a heater current of 0.7 A, for a heater power of about 4.5 W. A 10 VA encapsulated mains transformer with two 6 V secondaries makes a suitable supply. In theory the two heaters can be wired in series and a 12 V transformer used, but it is found that in practice the heater voltages are not then equal. An arrangement like that in **Figure 1** is better, where each valve is supplied from its own transformer winding. The two windings are nevertheless in series, and it is straightforward to generate a DC supply at about 40 V for the anodes from this 12 V AC supply: here we use a tripler circuit.

Amplifiers with and without negative feedback

The amplifier circuit in **Figure 2** shows a fairly typical class A output stage, as used in loudspeaker amplifiers. The anode currents do not flow through the output transformers, since the magnetisation caused by the DC component would lead to distortion. The audio frequency signal is taken via a volume control potentiometer to grid 1 (G1) of the valve. A 1 kΩ series resistor suppresses high frequency oscillations. The screen grid (grid 2) is at supply potential, while the suppressor grid (grid 3) is connected to the cathode. The output signal at the anode is coupled to the audio transformer via an electrolytic capacitor. Alternatively, high-impedance headphones may be connected directly to the coupling capacitors.

Compared to a triode, a pentode has a very high internal impedance. This is extremely helpful in designing the amplifier and allows inexpensive mains transformers to be used at the output.

The voltage drop across the cathode resistor provides for a negative grid bias voltage relative to the cathode. The operating point of the valve is set by this resistor. A value of 100 Ω provides a grid voltage of 0.5 V with an anode current of 5 mA. At the same time, the cathode resistor provides a certain amount of negative feedback and hence a reduction in distortion in the valve, without reducing the internal impedance of the amplifier.

A particular feature of this circuit is that the negative feedback can be disabled my fitting jumpers JP1 and JP2, bringing the parallel 100 µF electrolytic capacitors into play. This affects the sound and the output power of the amplifier.

The two characteristic curves — at an anode voltage of 40 V and at 250 V — exhibit a gentle curve and are very similar to one another. It is precisely here that the secret of 'valve sound' lies. If no attempt is made to straighten the characteristic curve using negative feedback, a certain distortion to the audio signal inevitably arises. These comprise harmonics and mixing products, chiefly odd multiples of the fundamental frequency, which are pleasant to the human ear. Since the ear does not work linearly at high volumes, a live concert at 100 dB(A) sounds better than a recording. With a valve amplifier the sound is also pleasant, more 'full', at lower volumes.

In the quiescent state, with U_g = –0.5 V, no grid current flows. When it is biased to 0 V the peak grid current can be up to 20 µA, which flows through the 100 kΩ volume control potentiometer acting as a grid leak resis-

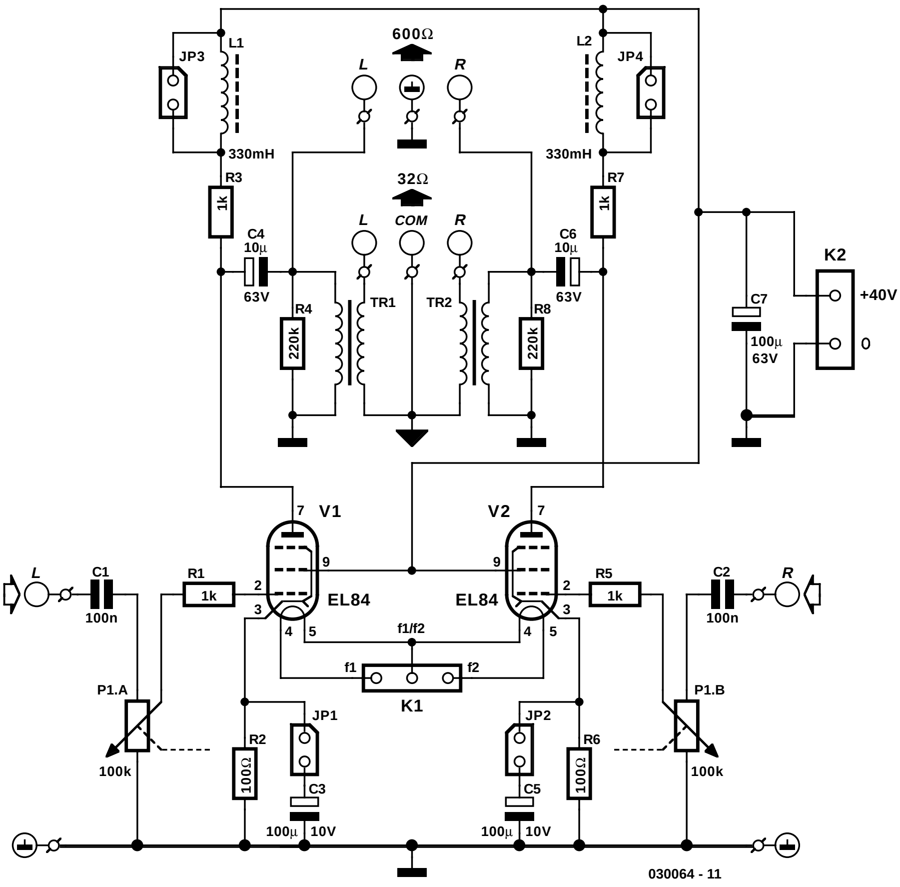
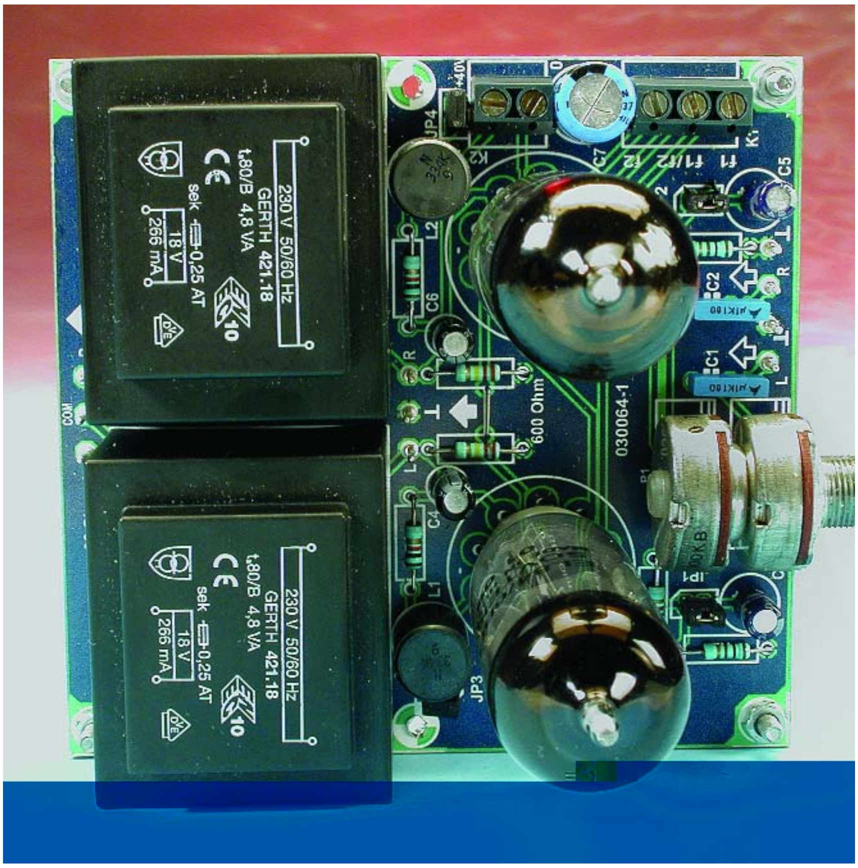


Figure 2. The amplifier with switchable negative feedback.

tor. A conventional power amplifier with a higher anode voltage would use a value of 100 kΩ to 1 MΩ here. At lower anode voltages this value is critical. Too high a grid leak resistance would result in an additional drop in grid voltage when a grid current flows. On the other hand, the input impedance of the amplifier must not be allowed to go too low, or it may not be compatible with the line output of ordinary hi-fi equipment. A 100 kΩ potentiometer provides a suitable compromise.

The subtleties of transformer selection

Another key to constructing a successful amplifier is the selection of the output transformer. A genuine audio transformer would have to be specially made for this application and would therefore be very expensive. For that reason, we shall use a readily-available mains transformer. Excellent results can be achieved as long as the right type is used. A mains transformer can handle frequencies above 50 Hz if it has a suitable core size and the windings have the right inductance and DC resistance.



Inductance

The output impedance of the valve is closely approximated by $R_a = U_a / I_a$. According to the EL84 data sheet, the valve should be operated at 250 V and 48 mA, implying an external impedance of around 5 kΩ. The data sheet actually recommends between 4.5 kΩ and 5.2 kΩ. At 40 V and 5 mA we obtain 8 kΩ. If anything, the value chosen should be lower rather than higher than this. Too low an external resistance leads to a lower AC component of anode voltage at the extremes of anode current. Since this means that the anode voltage is less likely to reach zero, the result is a lower likelihood of distortion.

Consider a transformer with a turns ratio of 230 V:18 V = 12.8:1. The impedance ratio is to a first approximation $12.8^2:1 = 164:1$. Thus a headphone impedance of 32 Ω is transformed into an external impedance of 5240 Ω. An 18 V mains transformer would therefore appear to be suitable.

This argument is valid only when the transformer is directly in the anode circuit. In practice the 1 kΩ anode resistors reduce the impedance of the circuit, and so for optimal matching a lower turn

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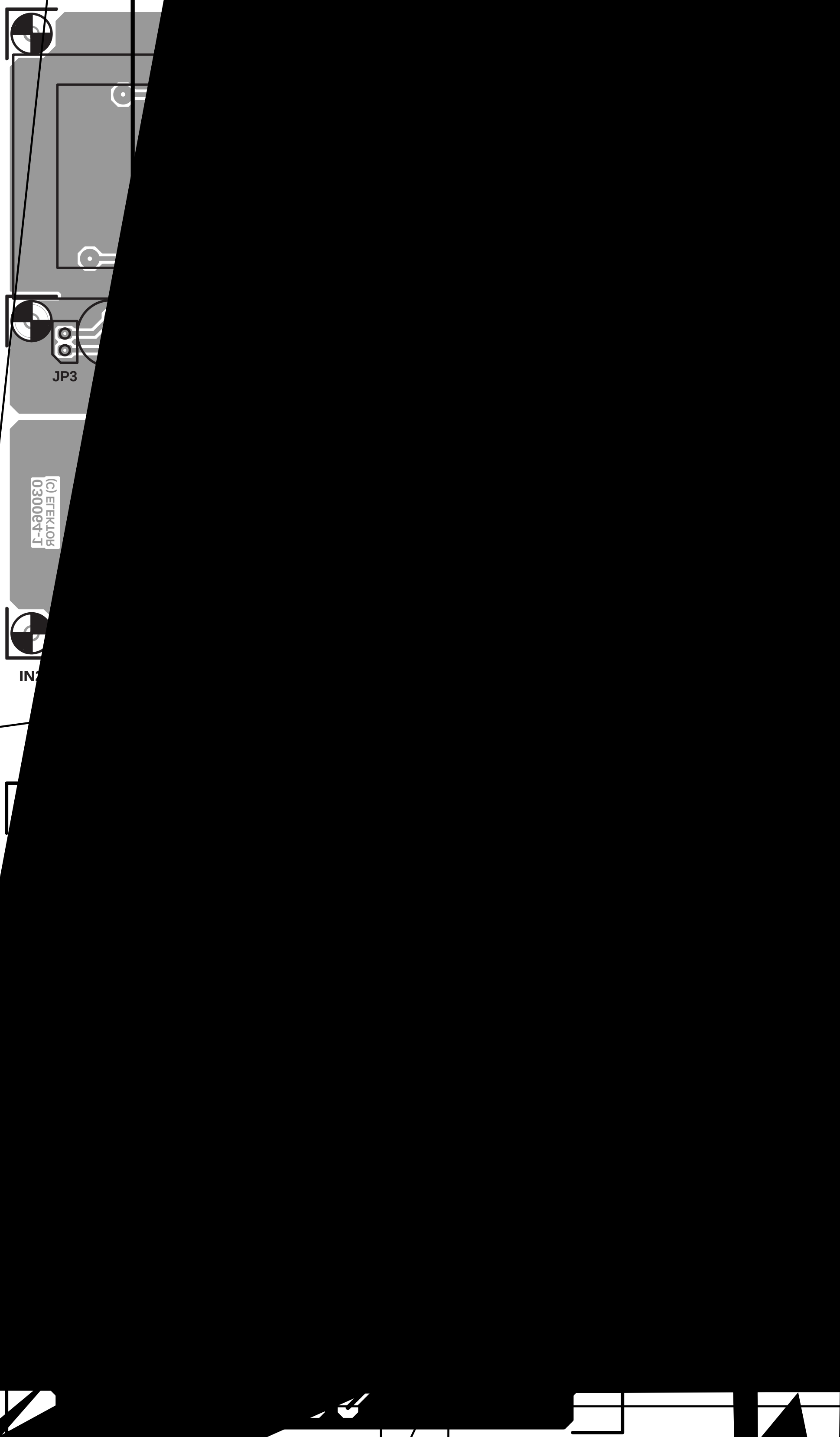
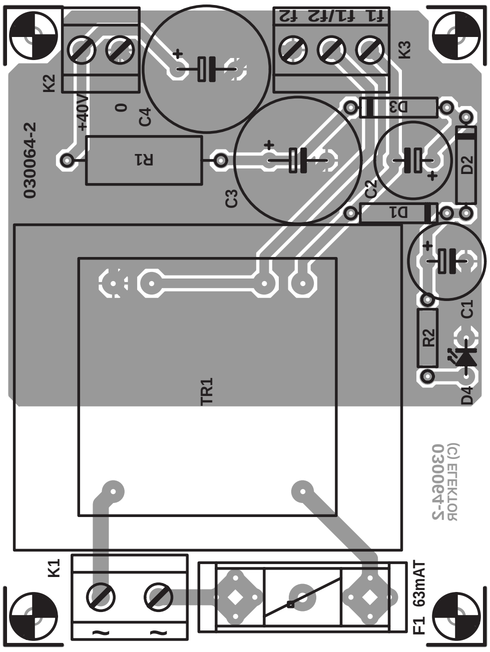
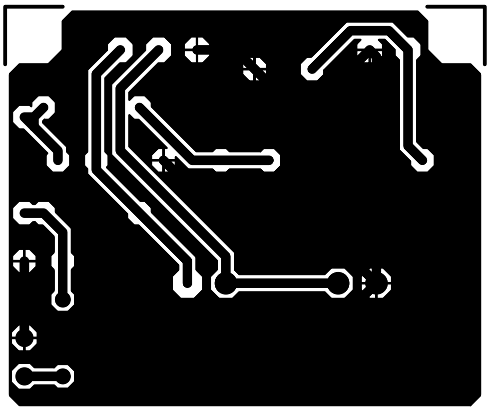
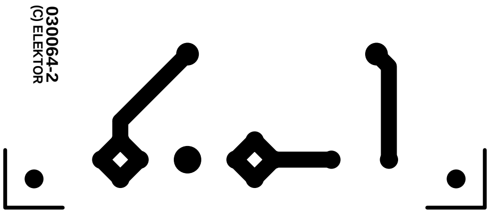
higher frequencies, whi



oard layout with separable 32 Ω section.







Characteristic curves

The characteristic curve in **Figure A** shows how the valve behaves at the reduced anode voltage of 40 V. Comparison with the curve from the data sheet (**Figure B**) shows similar behaviour, although only at rather higher currents. This means that we can use the EL84 in the same way as it is used in a valve radio, albeit with lower output power. Also, when using an anode voltage of 40 V, the grid bias voltage must be reduced.

Comparing the two characteristic curves shows that its position shifts at lower anode voltages with lower anode currents and lower grid bias voltages. The optimal operating point lies at around U_{g1} = –0.5 V and I_a = 5 mA. At full drive with an audio frequency signal of 1 V peak-to-peak the valve is then driven between –1 V and 0 V, giving an anode current varying between 3 mA and 8 mA.

When driven to around 0 V or slightly more, the grid current also becomes important. For this reason we also need to consider the grid current characteristic (**Figure C**), which in turn is somewhat dependent on the anode voltage. A higher anode voltage reduces the grid current, since free electrons are drawn more towards the anode, and fewer land on the grid.

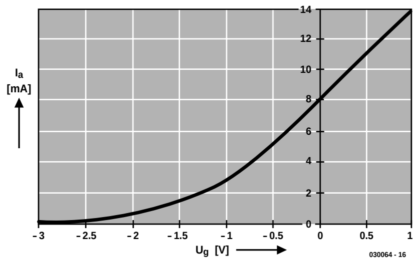


Figure A. Characteristic curve for the EL84 at $U_a = U_{g2} = 40$ V.

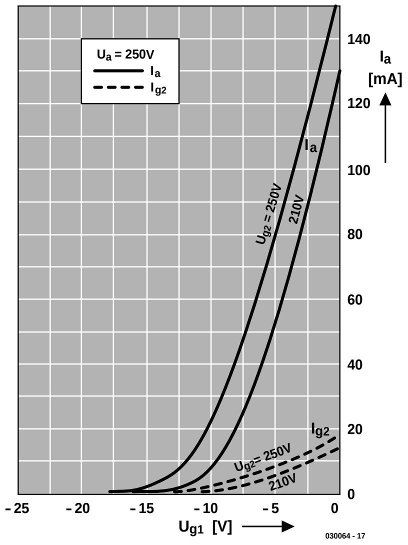


Figure B. Characteristic curve at 250 V.

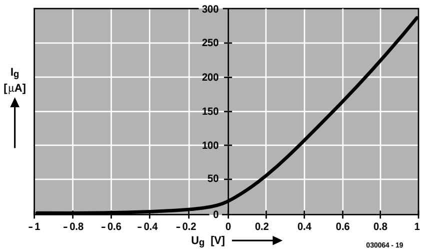


Figure C. Grid current up to U_g = +1 V.

when calculating the actual turns ratio.

A good choice is a transformer with an EI42 core and rated at about 5 VA. The Gerth 4200 range includes a suitable type (available for example from Reichelt Elektronik, Germany, order code 421.18-1). It is not too large, and, at about two pounds, not too expensive either. It will guarantee good sound quality with 32 Ω headphones.

High or low impedance?

A frequency response from 30 Hz to 20 kHz into low-impedance headphones is very good when it is taken into account that it is being achieved using an inexpensive mains transformer. The alternative would be a very expensive custom device using layered windings to reduce leakage inductance. The audio transformers used in professional valve output stages are large and expensive.

An alternative to these specialist transformers is to experiment with types designed to be connected to a 600 Ω output. An interesting possibility would be to try ordinary 100 V audio line transformers (such as Conrad Electronics order code 516104-77), which have multiple taps on the primary and secondary allowing the matching to be adjusted.

The effort in finding a suitable transformer for the output stage is worthwhile: 32 Ω headphones deliver a pleasant and warm sound, even though the frequency response is not as linear as in a transformerless

Cutoff frequencies

The equivalent circuit of the transformer in **Figure A** illustrates the connection of 32 Ω headphones. The wire resistance of the secondary can be considered as 10 Ω in series with the load. There is thus a total of 42 Ω across the output. The actual turns ratio of 9.8 : 1 gives an impedance ratio of $9.8^2 : 1 = 96 : 1$. The primary thus has an impedance of 4070 Ω + 875 Ω = 4945 Ω, say 5 kΩ. This value fits well with the theoretical vale of 8 kΩ, which, in the interests of a pleasant sound, should be regarded as an upper limit. The low frequency response is limited by the high-pass filter comprising this load resistance and the parallel inductance of 14 H (**Figure B**). The –3 dB point of this filter can be computed as 56 Hz. In practice, however, we measure a lower cutoff frequency of around 30 Hz. Presumably we can attribute this difference between theory and practice to the difficulties inherent in measuring the inductance of the transformer.

The upper cutoff frequency arises from the low-pass filter comprising the load resistance and the leakage inductance (**Figure C**). Using figures of 4945 Ω and 0.5 H, we calculate the cutoff frequency, rather disappointingly, to be 1574 Hz. A value in this range is indeed measured if the transformer is connected to a low impedance signal source. Fortunately the dynamic impedance of the valve is at least ten times greater than the theoretical load resistance (here about 8 kΩ). Since, thanks to coils L1 and L2, the signal source has an impedance of over 80 kΩ at the higher end of the frequency range, the theoretically calculated upper cutoff frequency increases to over 25 kHz. The leakage inductance also comes into play: at higher signal levels the valve more readily goes into clipping. In practice this is often not a significant effect, since the distortion products lie outside the audio range.

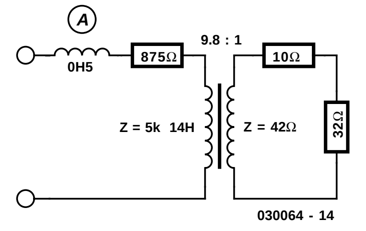


Figure A. Equivalent circuit of the transformer and load.

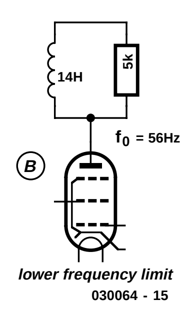


Figure B. Determining the lower cutoff frequency.

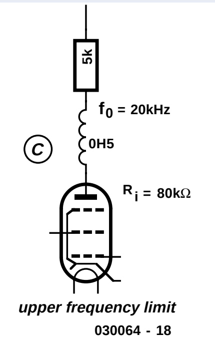


Figure C. Determining the upper cutoff frequency.

amplifier. None of these problems arises when using high-impedance headphones and capacitor coupling.

Do not forget to compare the sound with and without the cathode capacitors. The choice here is between lower distortion and more 'valve sound'. A little negative feedback will do no harm when listening to classical music in all its transparent glory; but rock music definitely calls for a bit of valve-style distortion.

Construction

The printed circuit board in **Figure 3** includes a section providing 32 Ω matching that can be separated from the rest of the circuit. There are no particular points to note about construction: there are only two wire links (near R4 and R6). If the Toko chokes cannot be obtained, types from other manufacturers can be substituted. Since coils over 100 mH are rare, it is also possible to use smaller values in series. Alternatives include:

Neosid BS75 (part number 00612436, 100 mH, 480 Ω, I_{max} = 5 mA, radial)
Fastron XHBCC (part number XHBC-104J-01, 100 mH, 245 Ω, I_{sat} = 60 mA, axial)
Epcos B82144-A (part number B82144-A2107-J, 100 mH, 420 Ω, I_r = 20 mA, axial)

Of course, you can also wind the coils yourself using an RM8 former and an N67 core.

If more output power is required, transformers with a higher secondary voltage can be tried. In this case, L1 and L2 will probably need to be adjusted.

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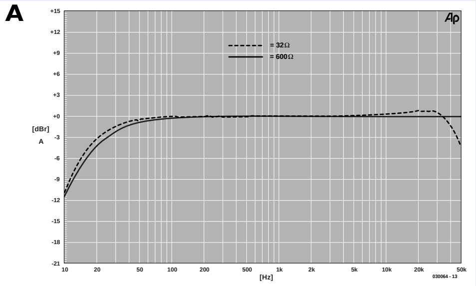
Frequency response



The measurement illustrated in **Figure A** shows the relative frequency responses of the amplifier with a 600 Ω load at the output (solid line) and with a 32 Ω load (dotted line). The curves were obtained with different anode voltages.

Input impedance	100 kΩ	
Sensitivity	600 Ω, 1 mW, JP1/JP2 open	620 mV (THD = 4.5 %)
	600 Ω, 1 mW, JP1/JP2 closed	370 mV (THD = 7.4 %)
	33 Ω, 1 mW, JP1/JP2 open	0.94 mV (THD = 7.5 %)
	33 Ω, 1 mW, JP1/JP2 closed	0.59 V (THD = 9.9 %)
Signal to noise ratio	600 Ω	>62 dB (B = 22 kHz lin.)
(1 mW, JP1/JP2 open)		>88 dB(A)
	33 Ω	>65 dB (B = 22 kHz lin.)
		>90 dB(A)
THD+N	600 Ω/1 mW	4.5 %
(1 kHz, B = 80 kHz,	600 Ω/0.1 mW	1.1 %
JP1/JP2 open)	33 Ω/1 mW	7.5 %
	33 Ω/0.1 mW	3.5 %
Bandwidth	23 Hz to >200 kHz (600 Ω)	
	20 Hz to 45 kHz (33 Ω)	