THE AUDIO TOOLKIT

Here's a project, or rather a series of adaptable projects, to solve those little audio problems or requirements that arise from time to time. By Graham Dicker.

Over the years, thousands of audio projects have been published and many constructors have assembled them with a great deal of success – only to find that they wish to modify or add some facilities to "personalise" the project. This usually requires that a breadboard-type circuit be constructed to provide the facility missing and if a pc board is not designed and made, then the mechanical reliability suffers. This is where the Audio Toolkit comes in.

A standard printed circuit pattern has been designed to provide a number of different single stage building blocks. They can be assembled in any number of modules up to a maximum of four or eight per board. There are five basic designs in the series, each with a different set of parameters and uses. All have been arranged with simplicity of design and construction foremost while offering staggering performance where required, even to full broadcast standard used by radio and television stations.

Let's take a look at the five circuit combinations.

Balanced input dynamic mic preamp

Circuit A is a high quality, very low noise, differential input, balanced line mic preamplifier. The circuit consists of a single stage BC549C transistor which has the inverting input from the Cannon (XLR) connector pin 2 to the base via a 4u7 tantalum capacitor. The use of good quality tantalum capacitors here is paramount to obtaining the noise figures as a standard electrolytic has far too much inherent noise and leakage. Should you wish to improve the noise figure, polycarbonate capacitors could be used if mounted on end.

This input is configured with the amplifier in common emitter with the stage gain determined primarily by the transistor h_{fe} and the collector resistor, R_C. The non inverting input comes from the pin 3 of the Cannon connector via another 4u7 tantalum to the emitter of Q1 in effectively a grounded base configuration. As the input signal is balanced, the effective base-emitter input voltage of Q1 is the total of the differential voltage from pins 2 and 3 of the Cannon socket.

While the common mode noise rejection ratio (CMRR) is not as good as most op-amps, this cirucit provides 60 dB (1000:1 ratio) CMRR which is more than adequate for the application and without the additional noise of a second transistor used in a more conventional two-transistor emitter-coupled differential amp design.

For those who are new to balanced line techniques, the principle in simple terms is that a professional microphone provides either a floating output from the insert or a balanced output with respect to ground with the phase of the microphone output voltage being 180 degrees between pins 2-3 of the Cannon socket. Provided that this phase relationship exists, then the amplifier will provide an output.

Should the microphone or cable have any noise induced (ie, from dimmers or nearby mains wiring) the amplitude of noise will be the same, and in the same phase, on both legs of the cable. If a differential amplifier or transformer is used at the other end, the common mode noise (interference) will algebraically cancel.

This technique is frequently used by commercial broadcasters to provide remote control and telemetry to and from transmitter sites without additional landlines. It is also frequently used during outside broadcasts to provide talkback, program back and cueing facilities.

ELECTRONICS
ETI 1432

SPECIFICATIONS, as measured on prototype

Frequency response +/- 3 dB	**1 Hz — 125 kHz**
Maximum output level	**+14 dBm (bridging)**
Normal output level	**+8 dBm (bridging)**
Headroom	**6 dB**
Distortion (THD) @ +14 dBm	**0.015%**
Distortion (THD) @ −10 dBm	**0.00125%**
Distortion (TIM)	**unmeasurable**
Signal/noise ratio wrt +8 dBm	**-118 dBm**

TABLE 1. SAMPLE GAIN SPREADS OF TESTED TRANSISTORS.

	GAIN									
	<400	400-450	450-500	500-550	550-600	600-650	650-700	700-750	750-900	>
BC549C	53	65	283	260	100	65	40	25	9	0
BC109C	0	3	11	285	220	221	142	85	16	17

What happens is this: a common mode signal is transmitted down the line between the single pair cable and the return signal formed by the ground return at both ends. This is commonly called a Hybrid or Kylo circuit as depicted in Figure 1. It is also possible to send dc levels down the line as well as the ac Kylo signals or to split the audio spectrum up for different purposes. One AM broadcast station used this technique for some months in place of two landlines when it first converted to stereo.

An interesting hint for those in the PA business: a number of my colleagues have in the past used figure eight (8) lighting flex with balancing transformers at both ends of the line in place of very long screened microphone leads, with considerable success.

The dc bias for the preamplifier is provided by a self-biasing 2M2 resistor between base and collector. This was selected to set the transistor's operating point to centre the collector voltage at approximately 12 V.

The BC459 transistors were chosen because of three main factors:
1) high gain, typically greater than 500,
2) low noise,
3) their h_{fe} provides pretty well an optimal input terminating impedance for a wide range of microphones, giving optimum power transfer.

Phantom-fed balanced mic preamp

This circuit, Circuit B, is identical in operation to Circuit A, with the exception of the addition of two 22k resistors going to the +24 V rail, and the reversal of the tantalum input capacitors.

Modern condenser (capacitor) microphones and some broadcast quality electret microphones are all externally powered by a nominal 24V supply; some early microphones require +48 V. In this case dc is fed to the microphone via both leads, bypassed internally within the microphone to provide its operating voltage. This is called phantom powering.

Audio output is sent 180 degrees out of phase on the two leads from the microphone. The dc is blocked by the tantalum capacitors and the audio coupled in the same way as in Circuit A.

Unbalanced mic or GP amp

A general purpose gain stage which can be used for a myriad of uses is shown in Circuit C. Applications include Baxendall-type bass and treble controls, compressors, expanders, limiters, etc. The voltage gain is set by the ratio of R_C to R_E. In the example given, the voltage gain will be approximately 100 (being 10k/100). Should you, for example, wish to have a voltage gain of 80 times, the required emitter resistor would be given by the collector resistor R_C divided by the voltage gain (Av):

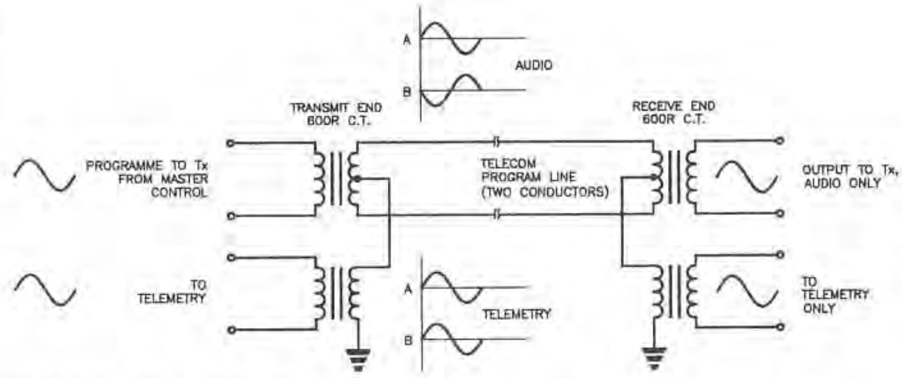


Figure 1: hybrid or Kylo circuit.

$$R_C/Av$$

or 10,000/80 = 125 ohms.

Depending on the peak-to-peak output voltage required, the base bias resistor (R_B) may need some adjustment.

The input impedance of this stage is equal to approximately

$$h_{FE} \times R_E$$

or in the case of the example
500 x 100 = 50k ohms.

It is worth noting that under most circumstances the value of the base bias resistor is usually larger than the transistor input impedance and as such may be ignored for the calculation.

Emitter follower

The emitter follower, shown in Circuit D, has many applications. This circuit has the same input impedance as Circuit C (calculated in the same way), and provides slightly less than unity voltage gain but substantial current gain as the output impedance is approximately $R_E/2$

The collector is bypassed to audio frequencies and the retention of the collector resistor limits the maximum peak-to-peak output voltage. For most applications in low level audio where the peak-to-peak voltages rarely exceed 2 Vp-p, the circuit will be quite useful. Should you wish to construct a conventional emitter follower the additional base resistor required between base and ground can be placed on the bottom of the pc board (the collector resistor can be bridged out with a link).

Simple headphone amplifier

This circuit operates in the same manner as Circuit C with the exception of a change of transistor type, no emitter resistor and a lower value of collector resistor. This stage has an output impedance of approximately 150 ohms and will produce a peak-to-peak voltage across a single 8 hm headphone of 1.2 V. This corresponds to a power level of 2 mW which will provide a 3 dB headroom above the maximum power rating of most headphones.

As the stage runs in pure class "A" it represents a good quality headphone amplifier for the digital era and is suitable for use with CD players, DAT recorders and as a studio or recording headphone monitor amp.

For home recording with the new generation of multitrack recorders available, a simple multiple output mixdown/foldback system could be constructed to enable each artist to receive a separate mix in their headphones.

Assembly hints

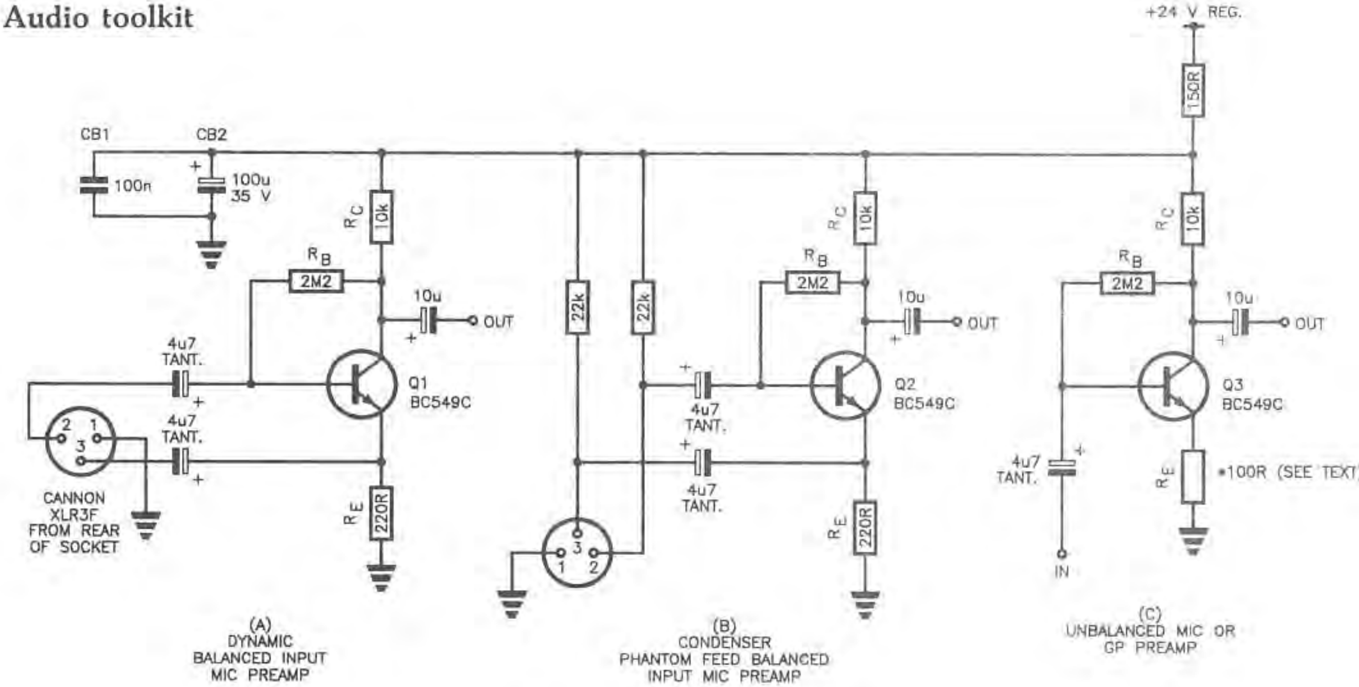
Before any modules are built, it is worth taking special note of the power supply. I have specified that this be derived from an external 24 V regulated source. This is necessary for noise-free operation of all low level stages as any ripple or noise on the supply would be readily amplified.

Two bypass capacitors are installed across the supply on the pc board, CB1 and CB2. CB1, a metallised polyester type, is used to effectively bypass any high frequency noise while CB2, an electrolytic, bypasses low frequency noise and prevents mutual coupling between stages which is the cause of motorboating. If the length of the leads from the power supply of the pc board exceeds 200 mm, the inductance of the cable becomes a factor to be considered, and the use of both capacitors is strongly recommended.

Because the basic board design is open, with well spaced component layout, construction is quite straightforward. Whether you make your own printed circuit board or purchase one ready-made, it is always good practice to check it thoroughly first. All the holes should be drilled out and of the right diameter to accept the component leads. See that no tracks are over-etched and possibly broken.

When mounting components, you can solder them in place in any order; just take care with the orientation of polarised components, such as the tantalum and electrolytic capacitors.

Orientation of the transistors should be quite clear. However you should check their pinout to see that the emitter base and collector leads coincide with the board layout. A quick foray with your multimeter in the ohms range or "diode check" will confirm which are the emitter and base leads, the remaining lead being the collector, of course.



Circuit A. Balanced input dynamic mic preamp.
Circuit B. Phantom feed balanced input condenser mic preamp.
Circuit C. Unbalanced mic or general purpose preamp.

In general, components should be mounted flush to the surface of the printed circuit board to minimise lead length. This provides mechanical stability and reduces stray coupling between circuits and possible pickup of R_F or extraneous hum or noise. Where an emitter resistor is not called for, as in Circuit E, simply bridge the two pc board holes with a short link of tinned copper wire. Just as you checked your pc board before assembly, it is always wise to check it afterwards, too. Check that components are in the right place and that polarised components are correctly orientated.

When you're satisfied that all is hunky-dory, you can connect a power supply and try out your circuit or circuits with real signals!

Design of a low noise preamp

Before this project was taken on, years of experience were taken into account for the optimisation of the design of the balanced line mic preamp. It may make interesting reading for those who build the projects to have a little more insight into the design stages that were undertaken and some of the unique methods that can be applied to design broadcast standard audio equipment.

Low noise mic preamps have long been an area for manufacturers of mixing desks to invest huge amounts of R&D. While the performance of a single channel may not pose a problem, as in the case of a simple hi-fi preamp, by the time you add the combined output of 16-32 channels the resultant noise figures can bring tears to an engineer's eyes.

It is because of this this that, generally, two areas are used as a compromise in designs. These are headroom and signal-to-noise ratio. If you have good noise figures, invariably the headroom is poor and vice versa.

Passive components. All passive components, particularly resistors, will generate noise so to optimise for minimum noise the highest quality resistors must be used, not necessarily for tolerance but for minimum generation of thermal noise. It has been found that Beyschlag 0.5% tolerance metal film resistors, or similar, offer advantages over cracked

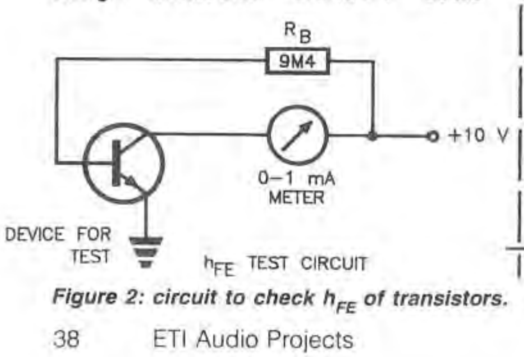
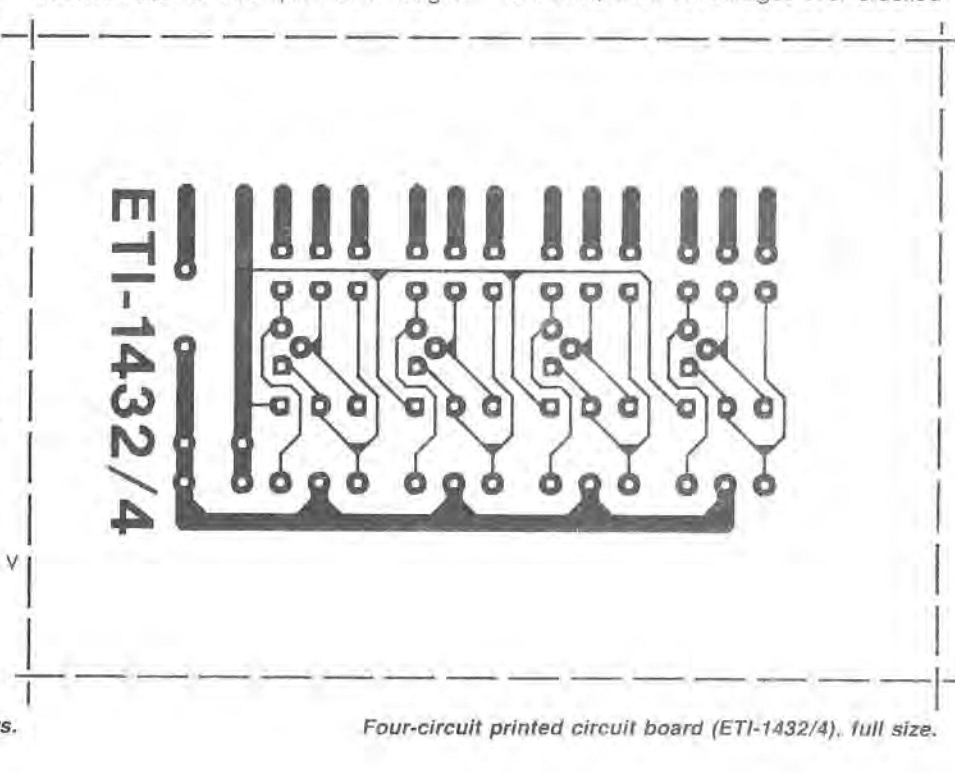


Figure 2: circuit to check h_{FE} of transistors.



Four-circuit printed circuit board (ETI-1432/4), full size.

carbon or composition resistors, with wire wound devices being a definite no-no because of their inductance and construction.

Capacitors are, again, another story, with electrolytics to be avoided because of their inherently high leakage and increasing impedance at higher audio frequencies. It is commonplace to find where electrolytics have been used in broadcast applications they are used with polycarbonate and/or disk ceramics connected in parallel to ensure a good impedance vs frequency performance.

Where large capacitances are required, for example interstage coupling, tantalum capacitors may be used, but these devices tend to break down and become noisy if for any reason they are reverse polarised. If the input impedance of the amplifier can be raised, then the use of high quality polycarbonate capacitors may be used as the capacitance values required are lower. This has been the choice of many designers today with the availability of BIFET low noise op-amps allowing the use of very high impedance circuits.

This may be very well, but the designer then must be careful of stray capacitances causing unwanted stability or bandwidth problems.

IC sockets should not be used as the least amount of contact resistance or dissimilar metals can cause rectification or noisy joints. The best solution is to directly solder devices to a good quality epoxy glass printed cirucit board, preferably double sided with the topside acting as a ground plane, and being constructed from 2 oz. or 4 oz. copper laminate, gold plated. (You also need an understanding bank manager!)

The use of laminated pc board with more copper can affect the noise performance of the design, especially at elevated temperature, and the thicker copper tracking will result in a lower resistance per square centimetre of track. Connectors of any sort are to be avoided, regardless of construction, for the same reasons listed above; the best solution is to solder everything.

Input transformers. Most high quality preamps use an input transformer to match the impedance of the microphone to that of the amplifier to ensure correct termination of an inductive source, for a flat frequency response, to provide a balanced input to the amplifier for good common mode noise rejection, and to provide an amount of voltage gain to improve the signal-to-noise ratio of the device.

This is a good design practice; however a good transformer will cost between $18 and $200 depending on the quality, and regardless of the expensive mu-metal shield incorporated, it will still have stray magnetic and electrostatic fields induced into its output. This is apart from the mounting and weight problems. It is also worth noting that all low noise preamps of any note have been frequently enclosed within mu-metal cases.

Earthing. The simplest and best designs can often be degraded by lack of care in design of the grounding systems employed for both modules and ancillary hardware.

Single point earthing is recommended for constructors with the common point being taken to ground separately with a short length of wire. In many systems, isolating the ground point then experimenting with a short jumper lead to find the best ground point can make a difference of up to 12 dB in noise figures. Also make sure that all input and output sockets are insulated from ground, and beware of one of my pet hates – chassis-mount RCA sockets! (If you must use them, put a grommet in the chassis hole to insulate them by other means.)

Potentiometers. It has amazed me how reputable designers of hi-fi equipment still continue to use lousy quality carbon track pots in their designs when the broadcast industry has for years been using quality conductive plastic faders, or even the antiquated but functional stud-type stepped faders.

Apart from the noise generated by the carbon pots, the mistracking between pots on a concentric shaft (stereo controls) is completely unacceptable for today's digital standards of 100 dB average head room. Surely the costs in quantity would be minimum.

On testing a batch of pots on my personal computer (I have written a simple program to display graphically the tracking of a pot's rotational position against resistance using the games port), of 100 pots only seven were to be found to be within 2% of each other, with the remainder all over the place. The only consolation was that the resistance from end to end was within 5%.

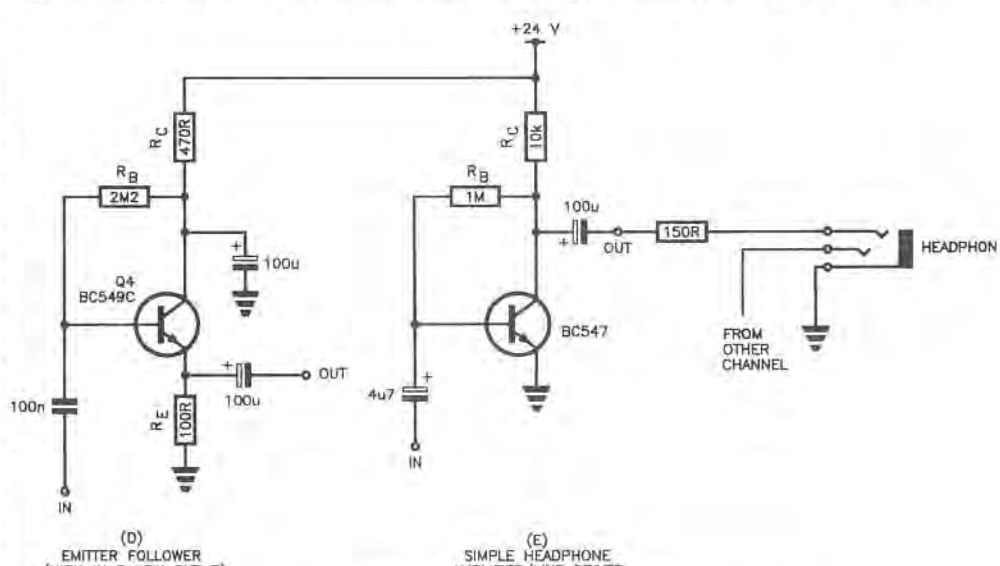
One could argue that, as our ears are logarithmic, who cares about trackability better than 10% as the difference is less than 1 dB in audio terms (1.41:1 ratio = 3 dB).

The problem is that, with the advent of digital equipment, the music headroom of 100 dB, plus the ambient noise level of 45 dBa, results in 145 dB range plus the scaling factor determined by the amplifier gain, all in 270 degrees of rotation of a gain control. While this may have been entirely suitable back in the days when vinyl disks reigned supreme, with CD and DAT now present this requires some rethinking.

Power supplies. The power supply rail (or rails) must be well regulated and filtered and if three-terminal regulators are used, they must be free from HF noise. The use of split supplies offers an additional advantage in that if any mains spikes do get their way through, then generally the spikes are equal and opposite in amplitude thus resulting in little or no change to the biasing of active devices and hence fewer clicks and plops in the output.

It is also vital that the mains transformers be well shielded to prevent stray electromagnetic radiation, toroids and "C" cores with copper shorting straps are recommended. If possible, mount the power supply in a different case away from the preamplifier stages. One of the best designs I ever tested used NiCads, which were charged when the unit was switched off.

Active devices. Op-amps are commonly used in preamp designs but suffer from two problems – noise and transient intermodulation distortion (TIM). With these designs it can be argued that you can't have both. Owing to the number of devices in the op-amp the rise time and transition time (propagation delay) through the devices



Circuit D. Emitter follower (high input impedance, low output impedance).
Circuit E. Simple headphone amplifier or line driver.

causes a delay before any feedback can be made effective. This results in the now well known TIM distortion.

For this same reason, the more devices in a circuit under feedback, the greater the noise introduced by each device and the greater the TIM. Among other factors, valve amplifiers usually have less than 12 dB negative feedback (due to limited open loop gain) and invariably had good TIM distortion figures. One point to remember – the noise figures will be degraded by every additional device put in circuit so the old rule of "keep it simple" applies.

Transistors have been around for years, and good ones are readily available at reasonable prices. The device selected for this series is the BC549, which offers good noise figures with high gain and excellent gain-bandwidth product figures. The noise figures do not vary greatly from device to device but the h_{FE} of the individual devices does.

In the units built for prototyping, 2000 transistors were purchased at an average cost of 6 cents each, then their gains tested with 1 mA of collector current. A typical breakdown of gains is listed in Table 1.

The first row shows BC549C devices (plastic pack), the second row BC109C (Philips metal can package). Of the 100 BC109s tested one had a gain of 1350 and, yes, it was functional.

To test devices a simple test circuit, as in Figure 2, can be constructed. The 9M4 base resistor can be made by connecting an 8M2 and a 1M2 resistor in series. The theory is that if a constant base current of 1 uA is supplied, a 0-1 mA meter in the collector circuit will directly read h_{FE} times 1000. If the h_{FE} is 1000, then exactly 1 mA of collector current will flow. If the h_{FE} is 500, then 500 uA (half a milliamp) will flow.

As mentioned earlier, the noise figures remain substantially the same between transistors, but the h_{FE} varies within a batch and in our prototypes we used the devices with gains of 750 or more.

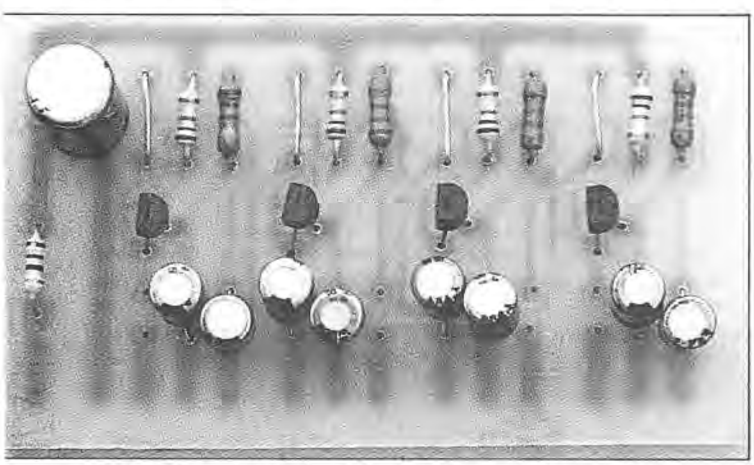
To design the preamp, the collector current must be noise optimised and from Figures 3 and 4 it can be seen that the noise figure changes with the collector current and source impedance. Here we are attempting to directly match a 500 ohm source impedance microphone with h_{ie}, the input admittance of the transistor (effectively the base-emitter input impedance), to get the maximum power transfer and to ensure correct termination of the microphone source impedance.

It will be seen that the noise performance is best in Figure 4 (at 10 kHz) and the Q point (quiescent, or dc, operating point) chosen is with a 600 ohm source. The collector current noise is optimised at 1 mA.

Figure 5 shows that at 1 mA collector current, the f_T (cutoff frequency of the device) is 125 MHz; in this case at least 1000 times the highest frequency required (100 kHz). Figure 6 shows that the h_{FE} at 1 mA should be typically 500 for an untested device.

The devices selected had an actual h_{FE} of nearly double this. It can also be shown from Figure 4 that the noise figure for these operations should be about 1.75 dB, which translates to approximately -120 dBm with an input voltage of 10 mV.

When you consider that an $18,000 NEVE mixing desk only quotes figures in the mid 90s, the performance obtained sets new levels and is suitable as a reference preamplifier. Once the collector current has been selected the rest is Ohm's law. **eti**



View of the printed circuit board of one prototype. This is a four channel headphone preamp.

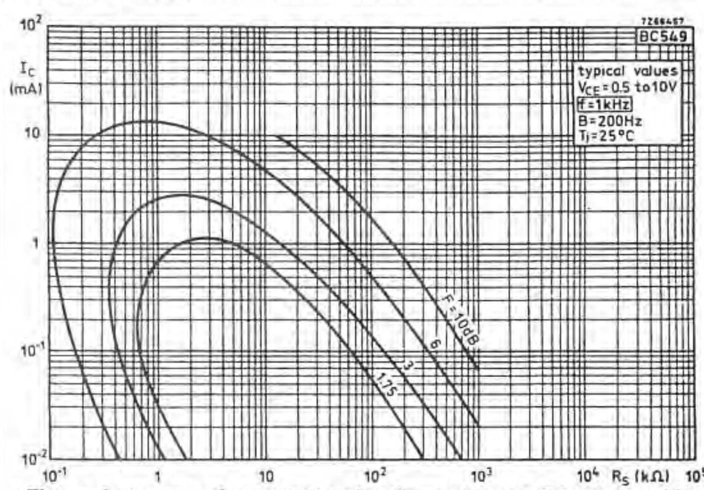


Figure 3: curves of constant noise figure for the BC549 at 1 kHz.

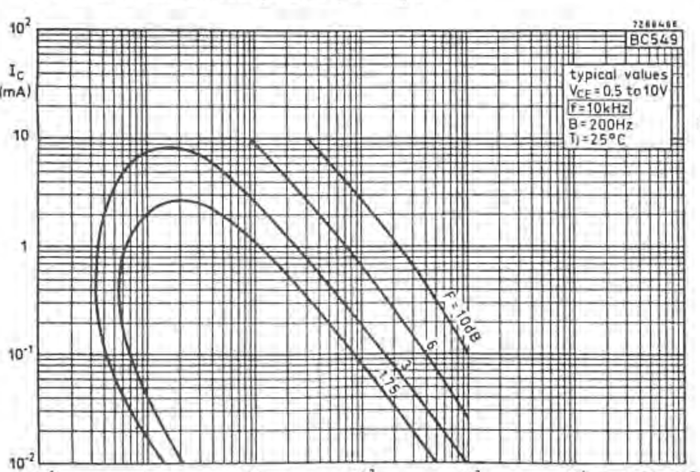


Figure 4: curves of constant noise figure for the BC549 at 10 kHz.

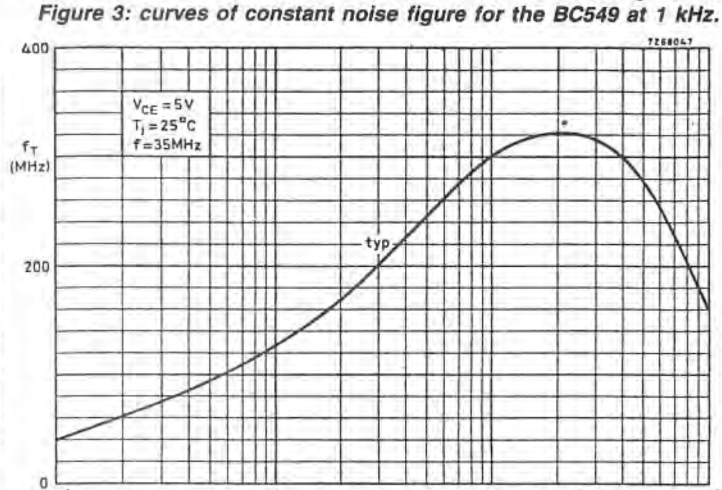


Figure 5: how f_T (cutoff frequency) of the BC549 varies with collector current.

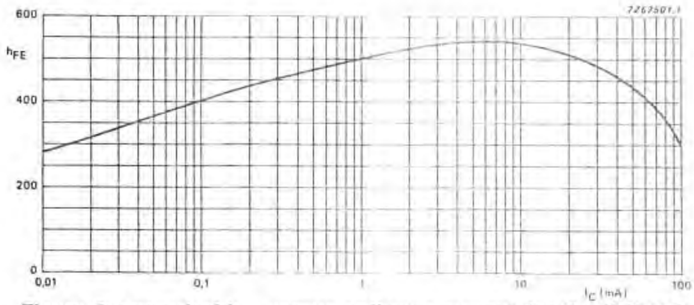
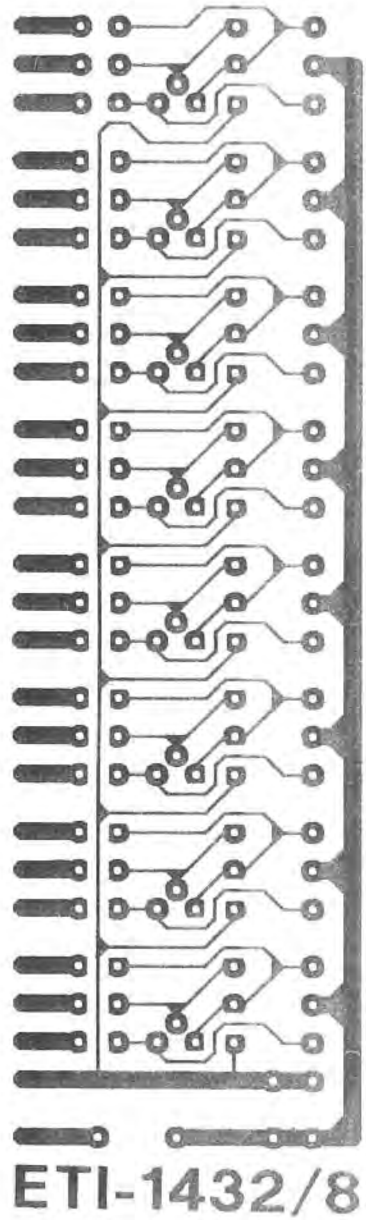
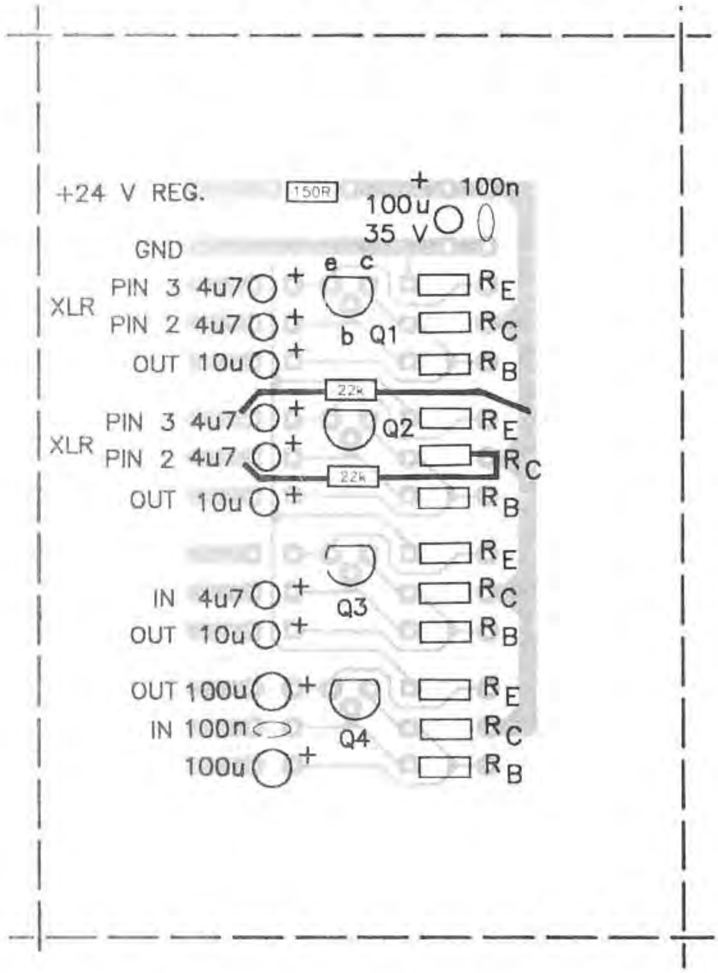


Figure 6: spread of h_{FE} versus collector current for the BC549C.



Eight-circuit printed circuit board (ETI-1432/8), full size.



PARTS LISTS — ETI-1432

CIRCUIT A
1 × BC549C or BC109C
1 × 2M2, 1/2 W, 5% (see text)
1 × 10k, 1/2 W, 5% (see text)
1 × 220R, 1/2 W, 5% (see text)
1 × 4u7/16 V tantalums
1 × 10u/25 V tantalum

CIRCUIT B
1 × BC549C or BC109C
2 × 22k, 1/2 W, 5% (see text)
1 × 2M2, 1/2 W, 5% (see text)
1 × 10k, 1/2 W, 5% (see text)
1 × 220R, 1/2 W, 5% (see text)
2 × 4u7/16 V tantalums
1 × 10u/25 V tantalum

CIRCUIT C
1 × BC549C or BC109C
1 × 2M2, 1/2 W, 5% (see text)
1 × 10k, 1/2 W, 5% (see text)
1 × 4u7/16 V tantalum
1 × 10u/25 V tantalum
1 × 100R selected for gain required (see text)

CIRCUIT D
1 × BC549C or BC109C
1 × 2M2, 1/2 W, 5% (see text)
1 × 470R, 1/2 W, 5% (see text)
1 × 100R, 1/2 W, 5% (see text)
1 × 100n/100 V polyester
2 × 100u/25 V electrolytics

CIRCUIT E
1 × BC547
1 × 1M, 1/2 W, 5% (see text)
1 × 10k, 1/2 W, 5% (see text)
1 × 150R, 1/2 W, 5%
1 × 4u7/16 V tantalum
1 × 100u/25 V electrolytic

MISCELLANEOUS
1 × 100n/100 V polyester
1 × 100u/35 V electrolytic
1 × 150R, 1/2 W, 5%
ETI-1432/4 or ETI-1432/8 pc board as required; input connectors as required; output connectors as required; tinned copper wire as required.