More Phase Inverters

1.1: Transformer Phase Inversion

The earliest push-pull amplifiers used an interstage transformer to drive the output valves, and this is still a popular choice among 1930s revivalists and fans of directly-heated triodes (DHTs). Transformer coupling was particularly convenient for directly-heated valves; the range of coupling capacitors available at the time was limited, a transformer could provide ‘free’ gain, and it simplified the problem of biasing the grid. This problem essentially disappeared once indirectly-heated valves and better capacitors became available, and transformer coupling is notably much rarer in the literature from 1938 onwards.

The coupling transformer typically had a step-up ratio of about 1:3, unless the power valve grids were to be driven positive for class A2/AB2 operation in which case a step-down ratio would normally be used, to achieve a very low drive impedance for the grids (e.g. <1kΩ).[*] The transformer might be directly driven by the previous stage like a small output transformer, or parallel-fed which avoids the need for an air-gap.

Various biasing schemes are possible,[1] some of which are shown in fig. 1. The simplest arrangement uses a transformer with a centre-tapped secondary. If cathode bias is used then the centre tap will be grounded as in a., or if fixed bias is used the centre tap will be connected to the negative bias voltage as in b. In either case the output valves’ grid leak path is through the transformer winding resistance, which is quite small. Grid-stoppers are shown to discourage oscillation, though early amplifiers often did without these to save money or to allow the grids to be driven positive. The load on the transformer secondary is only the Miller capacitance of the output valves, which will resonate with the transformer leakage inductance to produce a peak in the frequency response. Admittedly, this resonance will be damped by the source resistance of the driving valve, but an additional load resistance or RC Zobel network –represented by the impedance Z in the figure– can always be added too, to dampen it further, or to present a more appropriate primary load to the driver valve.

[*] In a push-pull amp, the Miller capacitance of the output valves can be neutralized. But in a single-ended triode amp with a step-up interstage transformer, the reflected capacitance across the primary might be as much as 1nF, which can be a considerable challenge for the driver valve.

[1] “Cathode Ray”, (1937). Practical Push-Pull Points, *Wireless World*, April, pp424-6.

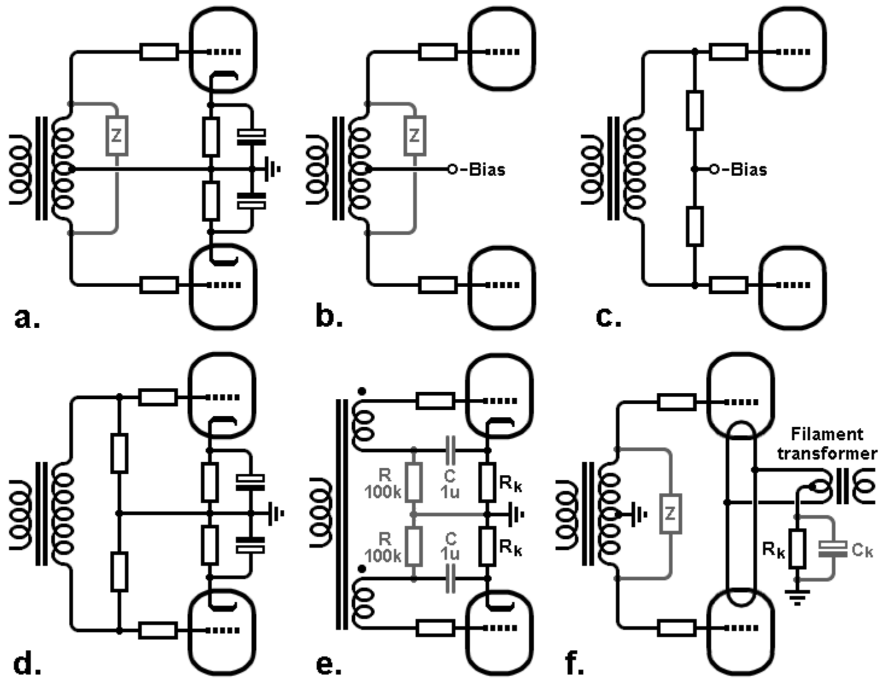

Fig. 1: Some push-pull biasing arrangements using an interstage transformer.

If the transformer has no centre tap then individual grid-leak resistors must be used as in fig. 1c and d. These might typically be 100kΩ, but any value could be used to reflect the desired load to the primary (provided it does not exceed the maximum allowable grid leak resistance of the power valves, of course).

Some designs used a transformer with two secondary windings as in fig. 1e. Each winding can be connected directly between grid and cathode of each output valve, so no cathode bypass capacitors are needed. Sometimes RC coupling was used, as shown faint, presumably because the designers were worried about idle grid current flowing in the transformer. This mayve been an issue for early DHTs with imperfect vacuums.

A more typical arrangement for DHTs is shown in fig. 1f, where both triodes share the same bias network (sometimes a humdinger pot was also included across the filament winding). However, shared cathode bias results in poor DC balance and also carries the risk of over dissipation in one valve if the other one fails or is removed from its socket. Some designs therefore used separate filament windings for each DHT, each with their own bias components.

Yet another form of transformer phase inversion is possible with an autotransformer. Since an autotransformer has only one winding it is easier for the manufacturer to minimise strays and create a better-quality component this way. Fig. 2 shows the direct and parafeed drive topologies; the output valves are shown cathode biased but they could equally be fixed biased.

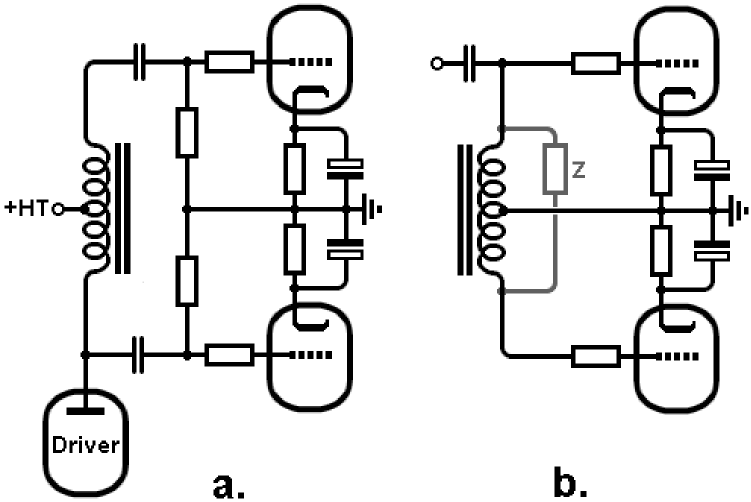

Fig. 2: Phase inversion using an autotransformer.

2.1: Paraphase

As transformer coupling became rarer it was succeeded by a simple inverting gain stage branching off the main signal path,[2] as illustrated in fig. 3. It has come to be known as the paraphase[*] inverter or paraphase valve.[3] This approach is intuitive, but primitive, since it has no inherent balance. The paraphase valve operates independently, so after tweaking it for perfect push-pull balance it will inevitably begin to unbalance itself as the valve ages. A few different variations on the theme can be found in early amplifier designs; the main issue is how to make the inverted signal the same amplitude as the non-inverted signal.

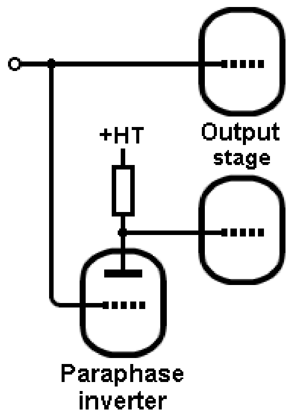

Fig. 3: The paraphase inverter in essence.

[2] Aughtie, F. (1929). Push-Pull Amplification: The Use of Resistance Capacity Coupling, *The Wireless Engineer*, June, p307-9

[*] *Para* as in *para*llel to the existing signal path. The name was first used in 1928 in British patent GB325833 but was applied other phase inverting circuits too, before more unique names were eventually settled on.

[3] Carpenter, R. E. H., (1945). "See-Saw" or "Paraphase"?. *Wireless World*, September, pp263-5.

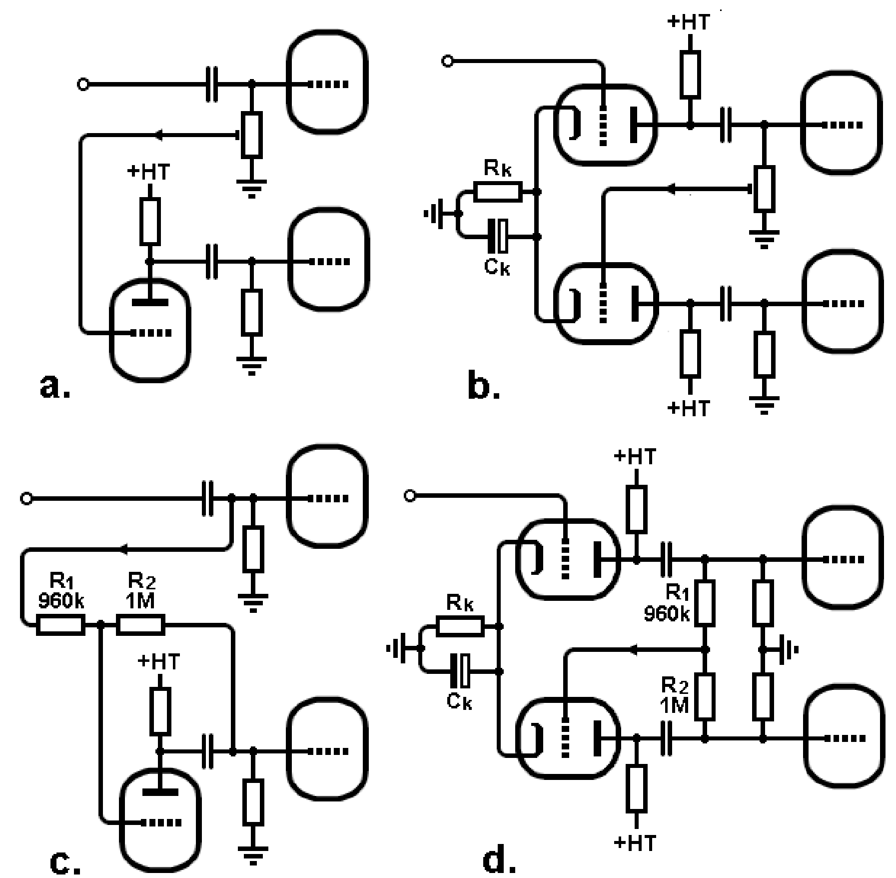

Fig. 4: Some variations on the paraphase inverter.

The first-principle approach is shown in fig. 4a. Here a potential divider or trimpot attenuates the signal before it is sent to the paraphase valve, which then amplifies it back up again (attenuating *before* amplifying ensures the paraphase valve will not itself be overdriven). The divider needs to attenuate the signal by the same proportion that the paraphase amplifies it, resulting in overall unity gain. In this case the power valve grid leak forms the potential divider, which economises on parts, but in some cases the signal was tapped off the anode resistor of the preceding valve stage.

In other examples† the cathode bias components of the preceding stage were shared with the paraphase valve as in fig. 4b. If the bypass capacitor C_k is omitted this can make the circuit appear superficially like some kind of short-tailed pair, but this is illusory. What this creates is closer to a Schmitt trigger. A shared (unbypassed) bias resistor effectively adds a small amount of *positive* feedback between the triodes,

† e.g. Fender *5A6 Bassman*

which increases distortion and makes the output impedances very mismatched. This does not really matter in a guitar amplifier of course; it was used in the Gibson *GA-20* and others, and in the Supro *1690T*, notably used by Jimmy Page for a while.

An improved version of the inverter is shown in fig. 4c. The paraphase valve is now configured as a local feedback stage or *anode follower*, and the whole circuit is sometimes called a 'floating paraphase'.[4,5,6] The topology is similar to how a modern opamp circuit would perform the same task, although here R_1 must be slightly smaller than R_2 to achieve perfect unity gain, because triodes have much less open-loop gain than opamps. The values shown are suitable for an ECC83 / 12AX7 but other valves would need some tweaking of R_1, or a trimpot could be used of course.[*] The local feedback minimises distortion in the paraphase stage and also makes the gain more constant in the face of valve ageing. Note that it gets its grid leak path through the power valve grid leaks.

If the cathode bias components are shared with the preceding stage we arrive at the circuit in fig. 4d. When drawn this way it does give the floating prophase an air of symmetry that might fool us into thinking it has some kind of inherent balance, but the paraphase valve is still just an independent anode follower. At least one author was caught out this way, describing the need for R_1 and R_2 to be "closely matched in value",[7] which is wrong. Omitting C_k would again introduce a little positive feedback that worsens the output impedances.

Although the paraphase is largely obsolete as a design choice, one possible advantage it may have in a guitar amp is that it allows a single pot to serve as a master volume for both power valves –as illustrated in fig. 5– whereas a dual-gang pot is usually needed with other phase inverters.

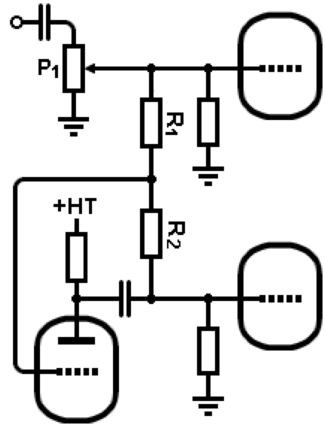

Fig. 5: Paraphase allows a single pot to be used as a master volume control for the whole output stage.

[4] Carpenter, R. E. H. (1930). Improvements Relating to Electron Discharge Apparatus. British Patent GB325833.
[5] Baxandall, P. J. (1940). High-Quality Amplifier Design, *Wireless World*, January, pp2-6.
[6] Crowhurst, N. H. (1959). *Basic Audio Volume 2*, p92. John F Rider Publisher Inc., New York.
[*] e.g. HH Scot *99D*
[7] Morley, W. G. (1965). Phase-Splitter Circuits, *The Radio Constructor*, November, pp234-7.

3.1: Bourget

Few have heard of the Bourget inverter, let alone used one. Indeed, it may only have been built by Bourget himself,[8] for the simple reason that it is not very good. But it is included here because it is a neat stepping-stone for understanding the Van Scoyoc inverter in the next section. Interestingly, Bourget's patent[9] was applied for in 1949, a year *after* Van Scoyoc published.

It is a simple observation that if we feed a signal into the grid of one valve and, simultaneously, into the cathode of another, the first will invert and the second will not. This is shown in essence in fig. 6a. Note that there is a positive DC voltage on the grid of V_2, which would be compensated for with a suitably large cathode bias resistor. The grounded-grid amplifier develops slightly more gain than the common-cathode stage, but this could be tuned out by running V_2 with slightly hotter bias, or by feeding a little of the input signal to V_1's grid, or by using mismatched anode resistors.

The obvious disadvantage of this circuit is that the input impedance of the grounded-grid stage will be very low, just a few hundred ohms. It therefore needs to be driven by a cathode follower, adding V_1 to the circuit in fig. 6b. Since the cathode resistor will be quite small, almost all the HT would be imposed across V_1, so a large HT dropping resistor and bypass capacitor have also been added, shown faint, to reduce dissipation in V_1. The obvious

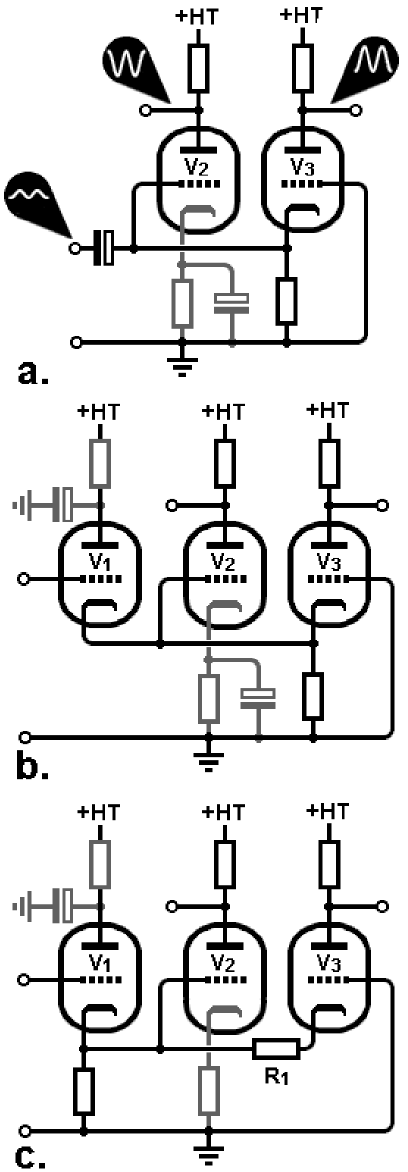

Fig. 6: The Bourget inverter is suspiciously similar to the Van Scoyoc.

[8] Bourget, L. R. (1957). Stereo Monaural Companion Amplifier for the "Preamp with Presence", *Audio*, November, pp19-22.
[9] Bourget, L. R. (1952). Phase Inverter Amplifier. US Patent US2618711.

disadvantage of *this* circuit (quite apart from using three triodes to make a poor phase inverter) is that distortion is likely to be high because the cathode follower is driving such a heavy load. The gain to each output will be fairly low for the same reason, and the PSRR and unbalanced output impedances are, well, unbalanced.

The application of this circuit was not principally audio, however, but video or DC amplifiers which require very wide bandwidth but are less troubled by harmonic distortion. This circuit already avoids Miller capacitance by using a cathode follower, but to push the bandwidth of this circuit down to DC we would need to remove the cathode bypass capacitor from V_2. This will also reduce the gain of V_2 of course, owing to degeneration, so Bourget's solution was to add a degenerating resistor R_1 to V_3 to restore balance, producing the circuit in fig. 6c. The circuit now looks suspiciously like a Van Scoyoc inverter with a bit missing.

4.1: Van Scoyoc

The Van Scoyoc[10] differential amplifier is a circuit that, at first glance, appears to be a contender to the long-tailed pair. It resurfaces on audio forums on a semi-regular basis, is discussed for a while, but usually peters out after everyone decides it uses too many valves. It enjoyed some popularity in America among hi-fi enthusiasts in the early 1950s,[11] but this did not last long. The circuit is shown in fig. 7 and is the same as the Bourget inverter but with an extra cathode follower, making it fully differential, with the two inner amplifiers being cross coupled. It is appealing for its symmetry, DC coupling, and ground-referenced inputs.

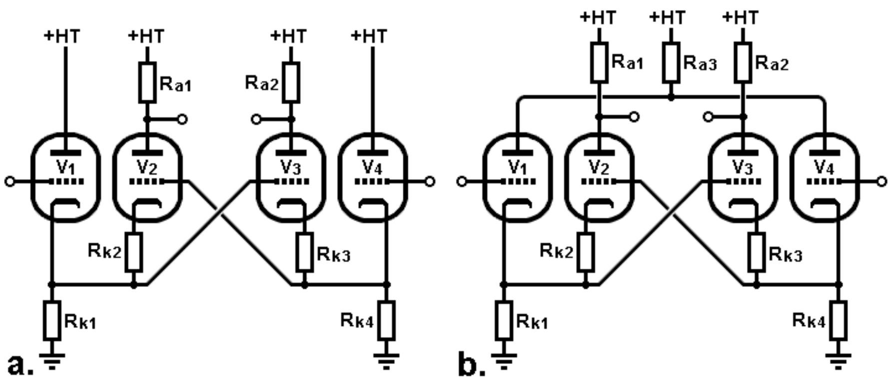

Fig. 7: Van Scoyoc differential amplifier. **a:** Original topology; **b:** Modified.

[10] Van Scoyoc, J. N. (1948). A Cross Coupled Input and Phase Inverter Circuit, *Radio-Electronic Engineering*, November, pp6-9. In this article Van Scoyoc also credits one C. W. Lampson for developing the same circuit independently, a few years earlier.

[11] Marshall, J. (1957). High-Fidelity Drivers and Inverters, *Radio-Electronics*, pp55-6.

As originally conceived, the two cathode followers have almost the full HT imposed across them, so a modification is to add a shared anode resistor R_{a3}, shown in fig. 7b. Not only does this reduce anode dissipation, it also introduces a small measure of cross-coupling between the cathode followers too, which improves AC balance and CMRR. This does reintroduce Miller capacitance when used as a phase inverter rather than a differential amplifier, but it is no worse than an LTP.

PSRR is underwhelming but still better than an LTP, the ripple at each output being the same as for a degenerated gain stage. The main shortcomings of the circuit are the number of valves used, distortion (owing to the heavy loading of V_1/V_4), and poor CMRR in practice.

The two pairs of valves need not be identical; typically the cathode followers will be a high-g_m device for low cathode impedance, while the inner amplifiers will be high-µ devices (or even pentodes) for more gain. For example, Van Scoyoc initially used 6SN7 and 6SL7 respectively, later 12AU7 and 12AX7.[12]

As a phase inverter one of the cathode followers is rather wasted, and it can in fact be replaced by a resistor equal to twice the nominal

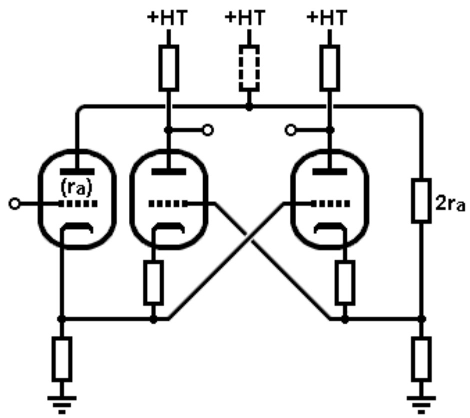

Fig. 8: Van Scoyoc / Bourget hybrid phase inverter, saving one triode.

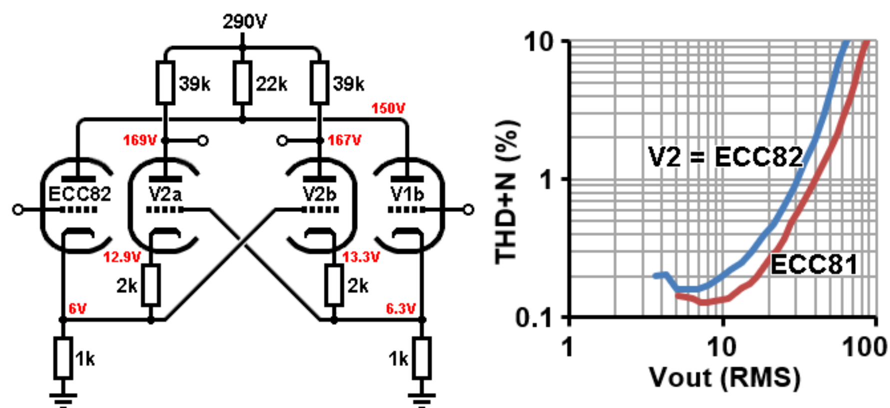

Fig. 9: Distortion performance of a Van Scoyoc differential amplifier.

[12] Van Scoyoc, J. N. & Warnke, G. F. (1950). A D-C Amplifier with Cross-Coupled Input, *Electronics*, February, pp104-7.

anode resistance of the remaining cathode follower,[13] as in fig. 8, creating a hybrid of the Van Scoyoc and Bourget topologies.

Fig. 9 shows the distortion performance of a Van Scoyoc differential amplifier using an ECC82 for the cathode followers. Distortion at small outputs is similar to what we would expect from an LTP, but the headroom is considerably worse. With ECC82s in both positions, differential gain was 7.2 and CMRR was a measly 30.5dB. Substituting an ECC81 into the position of V_2, with no other changes, resulted in gain of 10.3 and CMRR of 32dB. The problem is that CMRR depends for the most part on the valve matching of the cathode followers. An LTP side-steps this by forcing the current in each side to be substantially equal regardless of the valve characteristics, but here the two outer cathode followers are mostly independent of each other. Even slight mismatching between them demolishes the CMRR, no matter how well balanced the cross-coupled section happens to be. Really, the Van Scoyoc is more useful as a video amplifier or oscilloscope front end, where direct-coupling and wide bandwidth are a priority, but modest harmonic distortion and weak CMRR is not so troublesome

[13] DePalma, B. (1955). A High-Power Amplifier with Minimum Distortion, *Audio*, June, pp15-17.