Headphones and amplifiers: down the hill of impedance mismatches

Summary
Headphones are very sensitive devices (they require little power) but are actually very demanding due to the their ability to reveal every single detail of the records so low noise and precise amplifiers are mandatory. To make things more complex, the headphones do not have an easy and flat impedance across the audio spectrum and the matching with the amplifier may be unfortunate. Low and very low output impedance amplifiers can drive the headphones with accuracy and this is outmost important with the latest high sensitivity planars whose typical impedance is in the range of tens of ohm. The old rule of choosing an amplifier whose output impedance is as 1/10 or lower than the headphone impedance holds true.
Please note that the schematics in this paper are for example only and will require additional parts to work properly as an actual headphone amplifier.

A simple electrical model of the headphone

Headphone can be modelled as the resistance of the coil Rs and its inductance Ls that behaves like series component to the amplifier output. The cone can be represented by an electrical equivalent of parallel of the suspension compliance Lc, of the Moving mass Cc and of the mechanical damping Rc. This is an oversimplified model but it will work just fine for the sake of the discussion. The Rc-LC-Cc combination forms a resonant cell that reflects in the impedance chart of the headphone (see figure 2) and is one of the obstacles the amplifier must overcome.

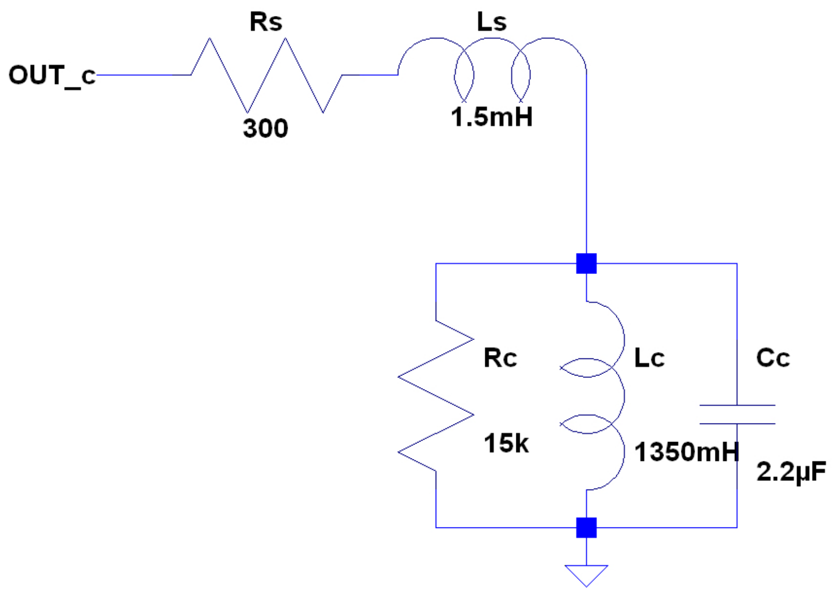

Fig. 1 A simplified model for a typical headphone with Rs and Ls coil paramenters and Rc, Lc and Cc that simulate the cone behaviour. This headphone has a 200ohm impedance.

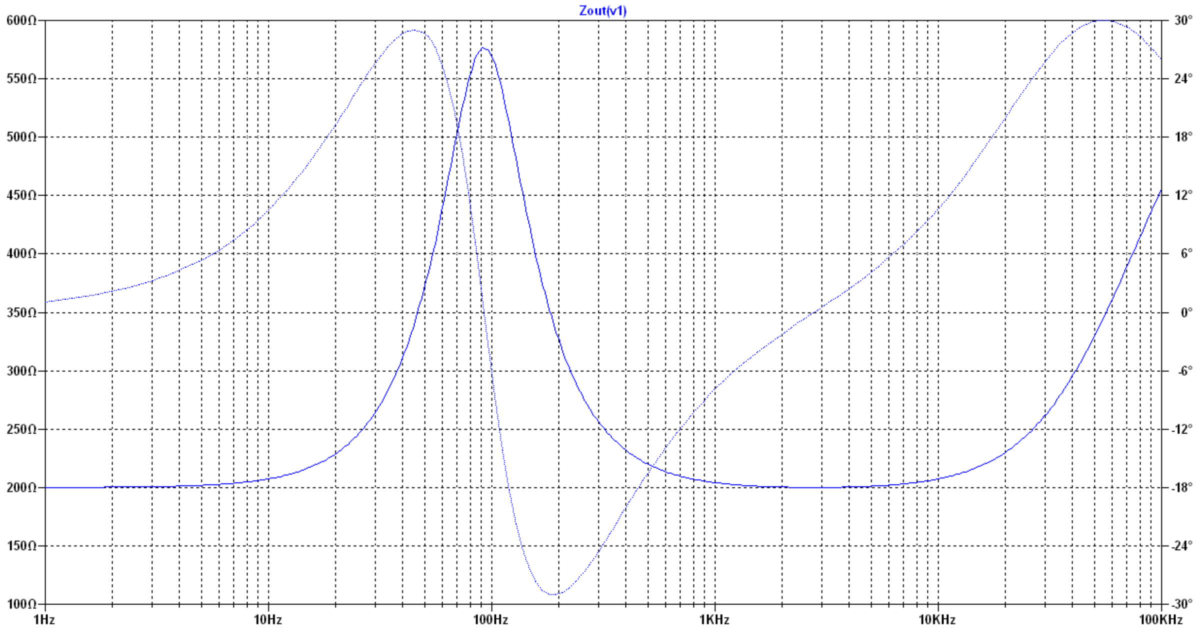

Fig. 2 Simulated impedance of the headphone. This model resembles a very typical real headphone with large peak at medium-low frequence. We may assume it has an average caratheristic impedance of 200ohm.

What happens in reality is that the output impedance of the amplifier will interact with the headphone impedance generating an uneven response over the audio band: namely the higher the headphone impedance the higher the output that will be generated (ie the sound pressure) by the headphone; this phenomenon is worsened by amplifiers with high output impedance. Below, in figure 3, the example headphone is driven by an ideal amplifier with variable output impedance: the violet curve is for a 600ohm output impedance, green for 200ohm, red for 10ohm and blue for 0.1ohm. It is clearly evident that the 600ohm amplifier will suffer of a 9dB insertion loss generated by the mismatch between the caratheristic 300ohm impedance of the headphone and its own output impedance. The 0.1ohm amplifier will be insensitive to the load and the combined frequency response will be ruler flat. Available amplifiers have generally impedances much lower than 600ohm and sit around 10-50ohm if using vacuum tube and 1-10ohm if based solid state devices or chip. There are exceptions clearly. Let's see in the following paragraphs a few examples of what the market offers in terms of typical amplifiers and how good/bad the matching with the example headphone is.

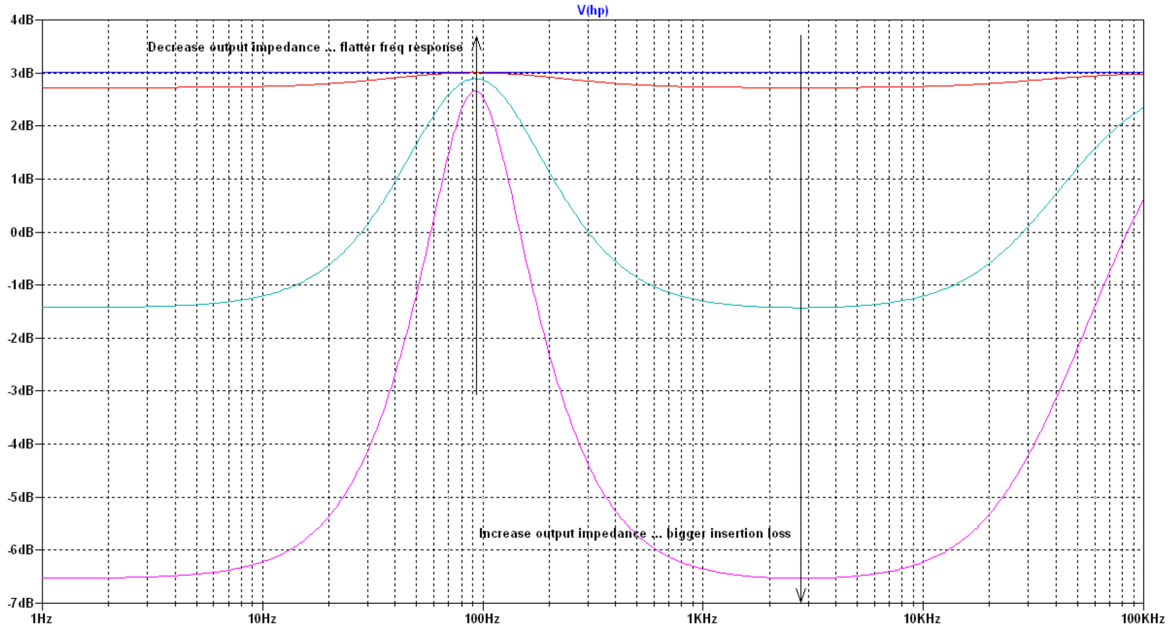

Fig. 3 Resulting bandwith after the matching headphone-amplifier for different output impedances (600, 200, 10 and 0.1ohm) of the amplifiers: higher output impedances cause an insertion loss (decrease of the average level) and a moderate to sever anomalies of the response.

A classic cathode follower amplifer (OTL)

Figure 4 represents a very common arrangement for an headphone amplifier: the first tube, U1, amplify the signal at the input and is directly coupled to the output buffer with gain=1 (the cathode follower) and 240ohm output impedance. Rs, Ls and Rc, Lc, Cc simulate the headphone in the model.

Unfortunately this solution requires a fairly large output capacitor that will make things a uneven at low frequency and will add some sonic signature to the amplifier. It is widely used in preamplifiers and headphone amplifiers and is also know as OTL (output transformer-less). I am using ECC82 as an example even thou output tubes with low gain and low impedance devices are preferred as OTL and often used in parallel to further lower impedance, but bear with me because in this case the output impedance of the amplifier is very close the the headphone impedance so it makes a great example.

As discussed, the resonance at 100Hz will be noticeable with a 5dB bump in the frequency response: that corresponds to a signal which is almost twice the average signal at other frequencies and can be classified as a very severe defect. You can also notice the increase in output above 10kHz due to the increasing impedance of the headphone and the drop below 20Hz due to the output capacitor of the amplifier.

If such an OTL was used with lower impedance headphones, things would be even worse with a severely limited response at bass and a large error at 100Hz.

Neither the headphone nor the amplifier are to be blamed, it is just a matter of a wrong matching of their impedances (240ohm from the amplifier to 200ohm of the headphone).

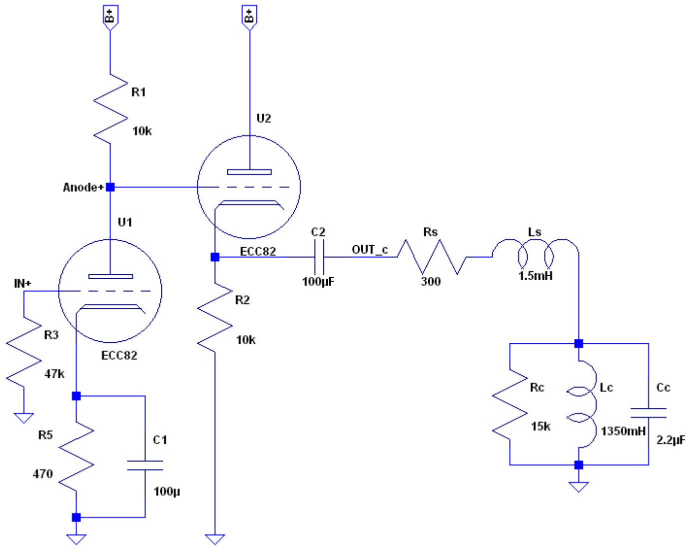

Fig. 4 A classic headphone amplifier with a tube gain stage and a tube buffer: output impedance of this amplifier is 240ohm. Use of more suitable tubes will lower the output impedance.

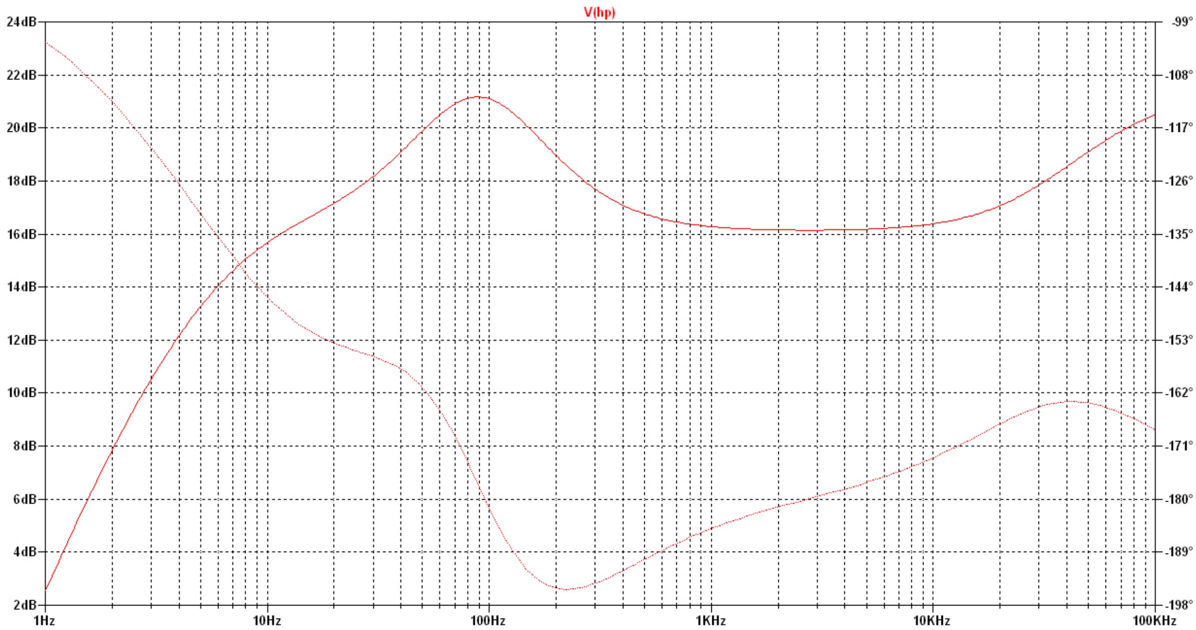

Fig. 5 the much ondulated resulting bandwidth of the cathode follower amplifier of fig. 4.

Vacuum tube and transformer

OTL’s are a cheap way to reduce the output impedance and create a sort of reduction gearbox to match the amplifying device (running at high impedance) with the low load of the headphone. A well know and audiophiles-loved solution is to use a expensive output transformer that reduces the output impedance (and the gain) of the amplifier. Figure 6 is a classical example with the ECC82, the output impedance is 40ohm but while an ECC82 may cost you 10-20 euro (plus a few more euros for the output capacitor) at current prices an adequate output transfomer may cost 100 euro each easily.

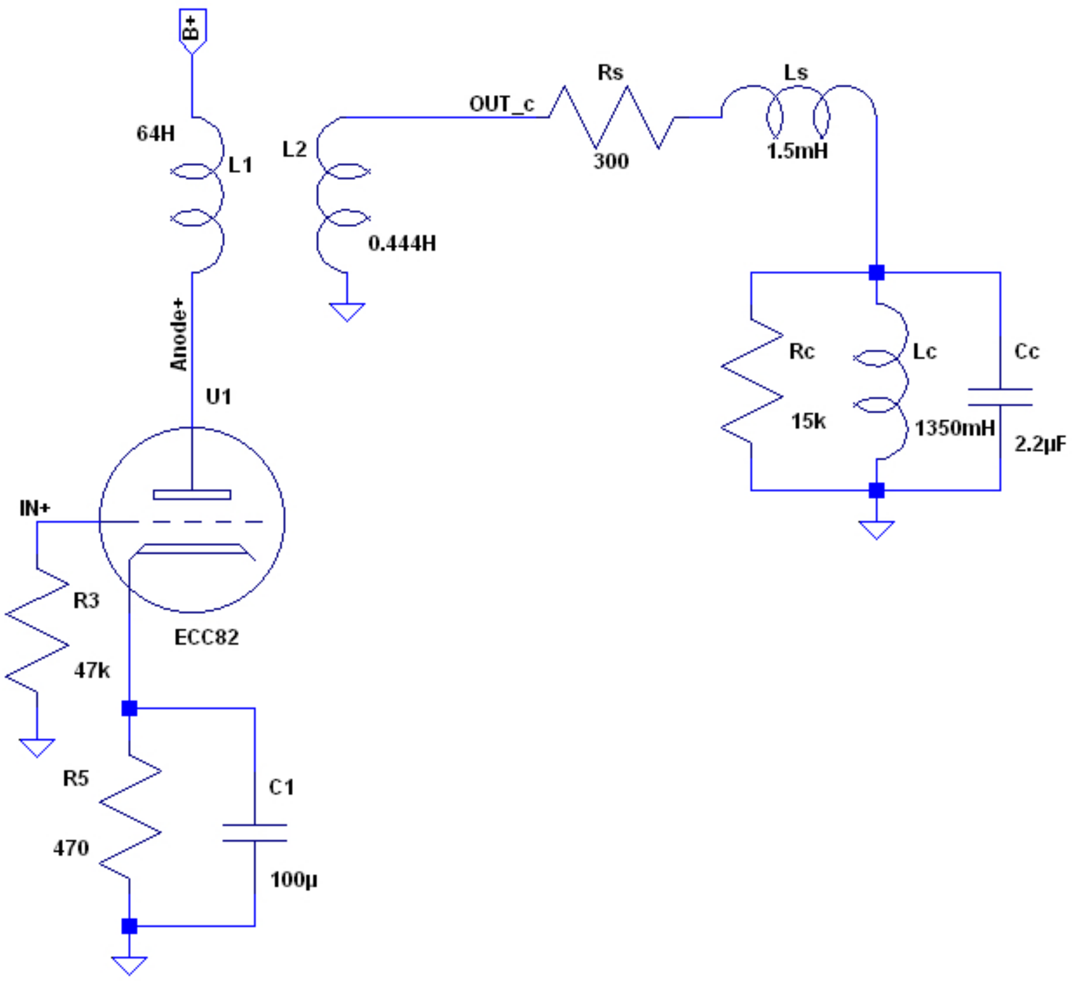

Fig. 6 Transformer loading of vacuum tubes can offer lower impedance and great sound. Output impedance of this configuration is 40ohm with a 12:1 transformer.

In figure 7 the simulated matching of the amplifier with the example headphone looks much better. The headphone to amplifier impedances ratio is 200/40=5 so still far from the 1/10 ratio mentioned in the summary so the 100Hz bump is limited to 2dB which might still be detactable by trained listeners. The drop of the response below 20Hz is due to the finite inductance of the transformer.
Soundwise, this solution is generally more transparent then the OTLs which are strongly imprinted by the large output capacitor that unfortunately has to be electrolytic. On the other hand the reduced gain (18x for the OTL versus 1.5x for the transformer coupled amplifier) may or may not be adequate to drive the headphone to full pressure so an additional gain stage may be required by this amplifier adding complexity and cost.
It is possible to design a lower output amplifier with transformer but that requires larger reduction ratio (ie 24:1 or higher) or lower impedance tubes that inevitably

have much lower gain. An option would be to use high gain (40x) and low impedance tubes (1kohm) such as the old Western Electric WE437A, WE417A, EC8010, EC8020, 6SC45pi and similars (WE and certain EC can be very expensive and hard to find): I do not personally like the sound of these tubes but their performace are hard to beat.

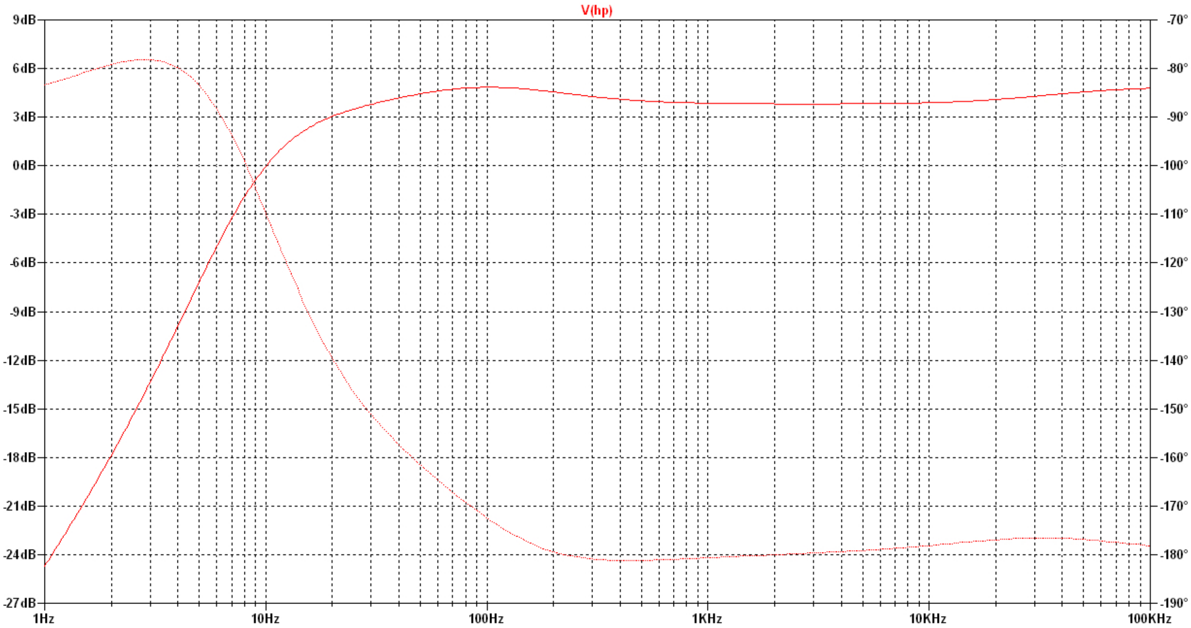

Fig. 7 The combinated response of the transformer based amplifer and headphone looks better than the previous example, the anomaly at 100Hz is now limited to 2dB. The drop below 10Hz is due the inductance of the primary winding.

State solid amplifiers

jFETs and MOSFETs can be very effective in driving headphone with compact dicrect coupled two stages arrangement exhibiting a very low output impedance, no coupling capacitor and reduced costs. Performances are instrumentally superior to vacuum tube amplifiers even thou many still prefer the sound of tubes over the MOSFETs.

In figure 8 a typical arrangement for a complementary pair of devices: the gain of this stage is 1, so they will need some additional active parts before them to make a complete amplifiers, and the output impedance is 0.4ohm.

In figure 9 a perfectly flat frequency response testifies the perfect matching of amplifier to headphone impedances. The bandwidth is very wide down into the lowest frequencies and up to ultrasonic spectrum, reality will be a bit less perfect.

MOSFET amplifiers require a 15-30V (dual) supply versus the 200-300V of tubes but they have the additional necessity of adequeate heatsinking to keep the device a safe temperature-

An other option is to use integrated chips that simplify the design (and furtherly reduce production costs) with similar or even better performances but soundwise they are somehow inferior according to the audiophiles taste.

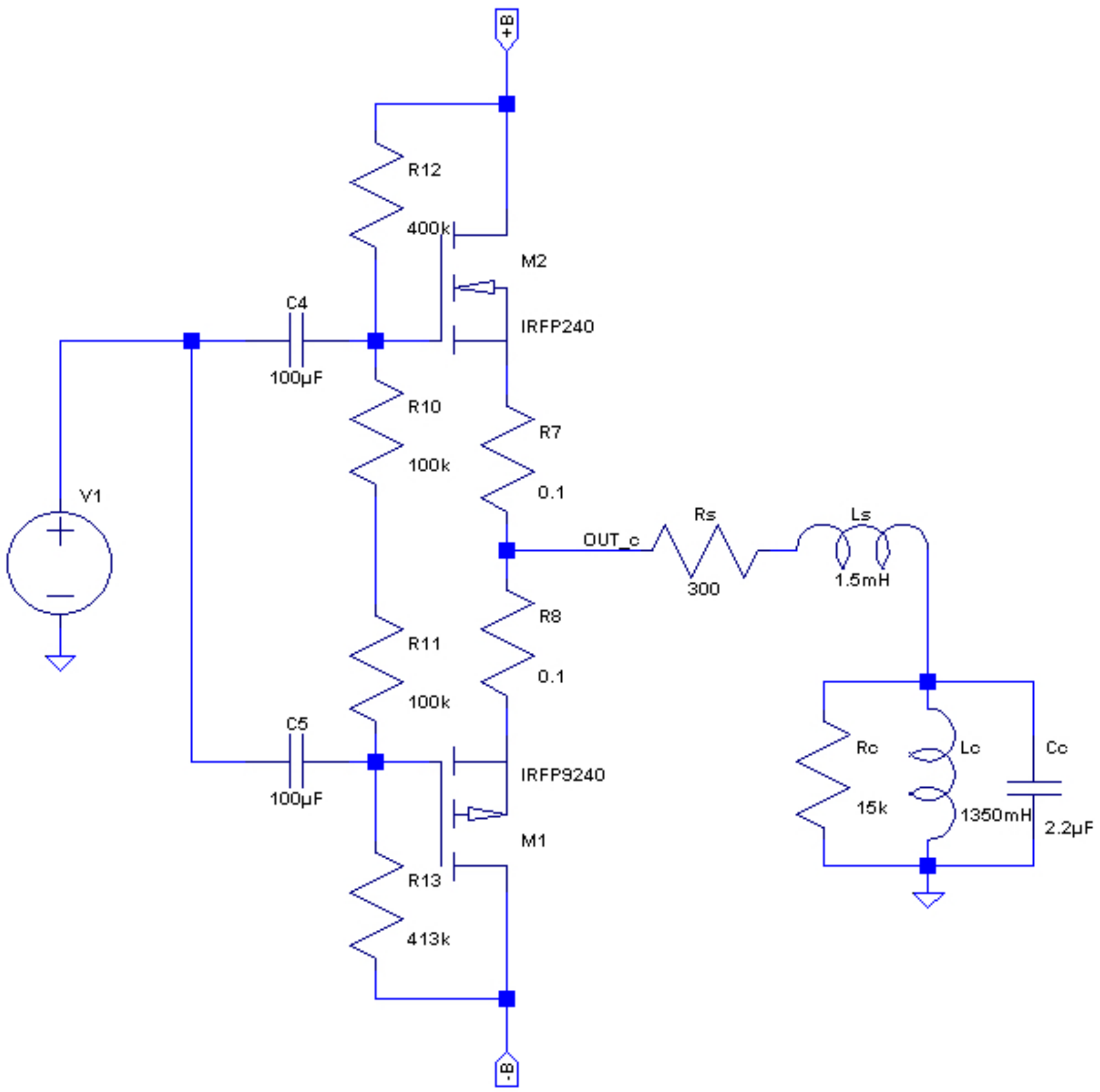

Fig. 8 A typical output complementary stage of a solid state amplifier, output impedance is 0.4ohm coupled with capability of swinging large currents into the load. V1 is the source

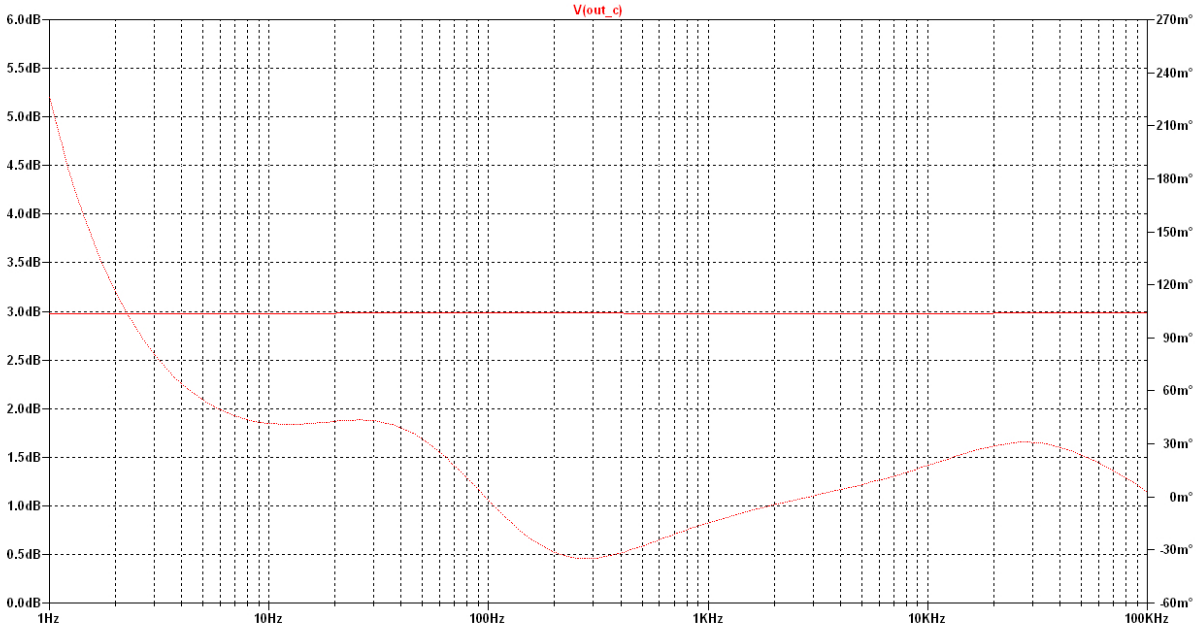

Fig. 9 perfectly flat response of the solid state amplifier with ultra wide bandwidth from DC to over 100kHz.

Our take on headphone amplifiers

It is no mistery I like vacuum tubes and jFETs but the benefits and advantages of MOSFETs can play a very important role too so it would come with no surprise if I used them all in an headphone amplifers. The SMA uses a differential gain stage based on tubes that sports very low loise and distortion and is coupled to an intermediate jFETs buffer capable of swinging the signal at the gates of the output mosfets overcoming their capacitance with ease. This solution blends the best of the available devices securing top performances and great sound quality.

In the next weeks we will also unvheil details of a newly designed headphone amplifier for the BeCubes lines.

Needless to say, reality is more complex and the headphone-amplifier matching is affected by other phenomena too and the design of an amplifier requires other tricks and tuning to perfect the end results.

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