ZGF Portable Headphone Amplifier

XEN Audio
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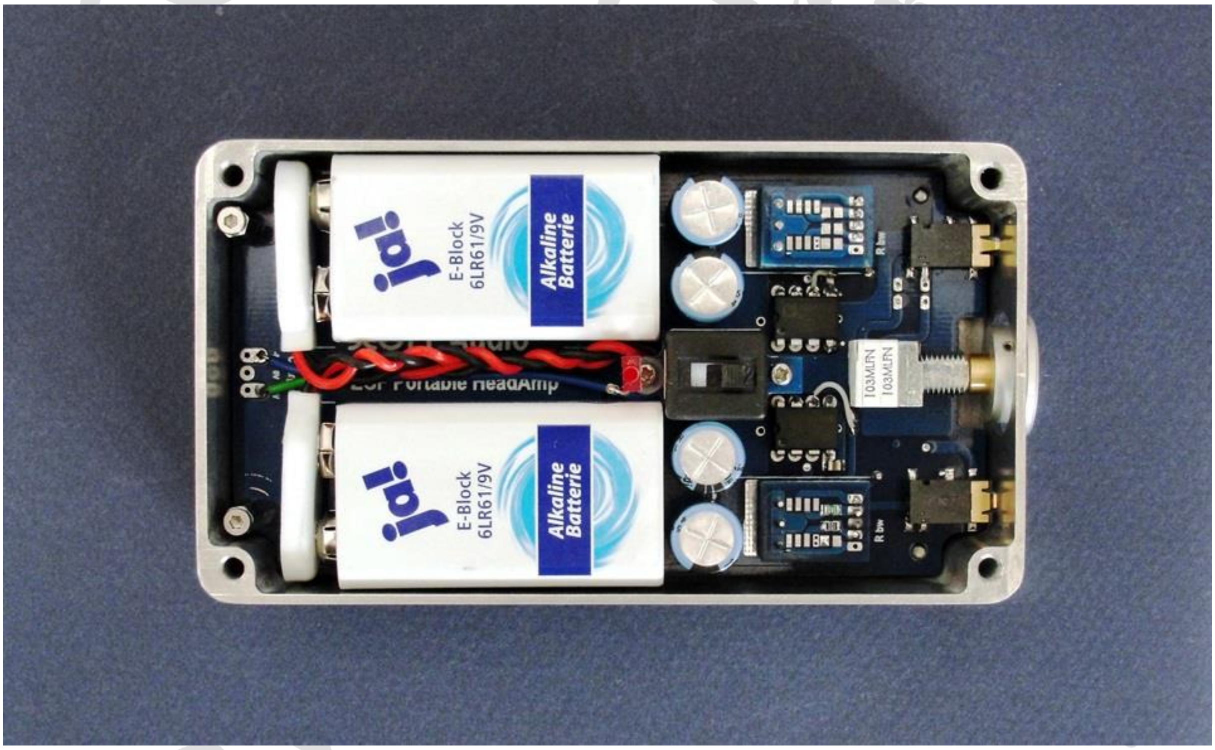


Background

I travel a lot by train. So I bought a Sennheiser HD25 Aluminium lately for some music on the road. Compact, light, robust, and above all, very good sound. But a small, portable, battery-powered headphone amplifier would be a good addition, especially if I want to use a micro SD Wav Player, or a USB DAC Stick with it later.

A word of warning. This is an expense-no-issue design. And it is more complicated than it looks. So if you are looking for a project for a beginner or on a tight budget, then you would probably be much happier elsewhere.

Circuit Design & Component Choices

The classic example of a portable headamp is the well published CMoy opamp based design. Lately there are other purposely developed headamp ICs such as TDA6120. They can all sound good, I am sure. Their good performance is normally achieved through a significant amount of negative loop feedback.

Nothing wrong with negative feedback. But if I take the trouble to design and build anyhow, I want to build something different, to follow the Zero Global Feedback (ZGF) approach of the DAO SE. Portability and low power consumption more or less rule out a fully discrete, Class-A build, and I also want it to be a “relatively” simple project. So I am willing to use IC’s for this once.

As in the DAO, there should be a ZGF gain stage followed by an open-loop buffer. So how to build a open-loop gain stage with IC's ? The AD844 comes to mind. The first I learnt about an "opamp" being used in open loop for voltage gain is the AD844 in the LC Audio MM Phono preamp [1]. Subsequent to that, there are a number of similar applications, but mostly using the AD844 in open loop as an IV converter. In fact, it was Jan Didden who pointed this out to be as we were discussing various configurations of my CEN IV Converter a few years back [2].

The way to use the AD844 as an open-loop voltage gain stage is to set the gain with two resistors, one at pin 2 (-Vin) and the other at pin 5 (TZ), and the signal is applied to pin 1 (+Vin). The ratio of the R2 / R1 gives the voltage gain. The AD844 is used as a current conveyor this way. To maintain low distortion, one should only swing a fraction of the 1mA that it is capable of. So let's design for a maximum output of 5V, and a maximum current of 250µA. That gives 20k to Gnd at the TZ pin. For a gain of 5x, the inverting input should see 3.9k to Gnd.

For delivering current to the headphone, there are quite a number of diamond-buffer type ICs on the market, BUF634, HA5002, LME49600, … to name a few. Some are obsolete, or becoming obsolete, the one remaining (BUF634) has gotten really pricy recently. But they have a few features worth having, such as very high Zin and low Cin (they help to preserve bandwidth with AD844's 20k Zout), which is not always easily to achieve in discrete buffers. There are also internal current limits and thermal protection, etc. which come in handy for a portable device.

AD844 + BUF634 is nothing new !! True. A very similar application is a Russian MC preamp design [3]. Here the AD844 is used with a gain of 200, with a single BUF634 as output buffer. And there is actually a headamp design based on this exact IC combination [4].

Initially, I also intended to use just a single buffer IC in DDPAK package (also for LME49600 which is now end-of-line). It allows good thermal conductivity to the outside world, and will deliver 250mA, more than sufficient for any travellers' headphones. This is also the basis of the PCB design. However, on closer examination, these devices only allows a maximum bias of about 15mA even at high bandwidth mode. Their Zout is around 7.5 ohm. So if you have one of those 20 ohm headphones, performance is not going to be great.

I found a couple of sites that provide some measured data of these buffers in open loop [5,6]. To have decent performance, one should really have enough bias to guarantee Class A operation. For my own application, I think ±3.5V into 70R is more than enough, and that means 50mA maximum output current, or 25mA bias. In theory 2x BUF634 in parallel will be sufficient, but I also like to have a Zout of 2.5R maximum. That would mean 4x BUF634 in parallel, each biased at 6.3mA. This can be adjusted by the bandwidth control resistor, and needs to be trimmed for each device. Test shows that the nominal value is around 300R. With 4x in parallel and in combination with AD844's Zout of 20k, the -3dB bandwidth of the entire circuit is still a good 125kHz. You can trade bandwidth for distortion by varying the number of buffers in parallel. And you can of course solder two or more AD844s on top of each other (in parallel) and reduce the values of the gain-setting resistors accordingly to increase bandwidth.

So done ? Not quite. Firstly the input bias current of the AD844 will create some DC offset at TZ. But even worst are the input current and output offset of the buffer IC's. The input current of a BUF634 is typically at 2.5µA per device, so 4x in parallel makes 10µA. And on 20k source impedance, that makes 200mV. On top of that, the output to input offset can be as bad as ±100mV according to data sheet. Definitely not OK.

That means firstly we need to measure them individually and try to group them according to the Vo/Vin offset. And a small 1R resistor could be added at the output before paralleling (even though in theory the 7.5R internal Zout will keep inter-chip current in check after matching). To take care of the input current offset, one can first measure the offset value in circuit at the TZ pin of the AD844, and then use a suitable resistor between TZ and one of the supply rails to cancel the offset. The value of the resistor is simply given by (20k x Vs / Vos). So say Vos is 20mV, Vs is 9V, the offset trimming resistor is then 9M. And PSRR will be 53dB. One can also try to make a low noise 1µA current source instead to improve PSRR. It will probably take up more space and be noisier, and not much better in dynamic impedance. And the single trim resistors works just fine in my first prototype.

After measuring some 20 BUF634s, the worst DC offset is about 30mV. That is still within the scope of trimming as described above (then in combination with the offset of the AD844 itself). But the offset due to the input bias current is proven to be as large as predicted. Even worst, it drifts with temperature and time. The 10µA itself is not really a problem if it were not coupled together with the 20k Zout at pin 5. I decided to choose a robust solution and use pin 6 instead to drive the BUF634's. The diamond buffer has a bad name because it does not have a lot of bias. But then we only need to drive 10µA and 2M // 32p. If one uses a single BUF634 or LME49600, or even a LH0033 (with JFET input), then pin 5 is just fine. The PCB provide both options with a solder dot.

Instead of using the trim resistor, I added an optional servo to take care of the offsets, as it will also compensate for DC drift with temperature and time. The servo opamp should be low noise, have JFET input, low input offset, rail-to-rail output, and be in SOT23 package. The OPA140 fits the requirements nicely. To reduce the noise of the servo opamp further, the servo circuit should have a high Zout. So I added a 200k resistor at the opamp output. That however limits the max. offset compensation to ±800mV, before the opamp runs out of voltage.

For simplicity, compactness and easy handling, I choose to use 2x 9V NiMh batteries for power. These are now available up to 300mAh. There are also lithium versions of the same size but 500mAh or more. Even with 300mAh, I get more than 3.5 hours between charges.

It is not easy to find a good but small pot for volume control. We like the Vishay Sfernice P9 a lot. It is of conductive plastic, as opposed to carbon film of the ALPS RK09x, but at 10x the price. Well, I think spending around 10% of the total project cost on a pot, which is in the direct signal path, is still a very good investment.

You can of course just use a 10k stereo log pot, but you may also consider using a 50k linear pot with a parallel resistor instead. The latter though has at certain positions a lower Zin and a higher Zout. Something to keep in mind [7].

The entire hardware fits nicely into a Hammond 1550B die cast aluminium cast, which I also use to act as a heat sink. One can always use a compatible or slightly larger case instead, but I like the compactness and light weight of the Hammond. And it is also not expensive. ☺

Cross-feed option

We have reported the successful use of the modified Linkwitz and modified Danyuk cross feed circuits for our DAO SE and our F5 Headamp. Both of these can use the same circuit but just different component values, hence also the same PCB. A mini-version of the Danyuk was designed as a daughter board, using SMD components. And to retain the ZGF design, this uses matched 2SK209GR's as output source follower. The penalty is 8mA additional current consumption. But 2x OPA140 as unity-gain buffer will also eat up 4mA, and will not be ZGF anymore.

Our standard cross feed design has a passive filter followed by a buffer. The filter is best driven by a low impedance source, so it makes sense to place it in front of the pot, the latter then being driven by the source follower. This is the same layout as in both the DAO SE and the F5-HA.

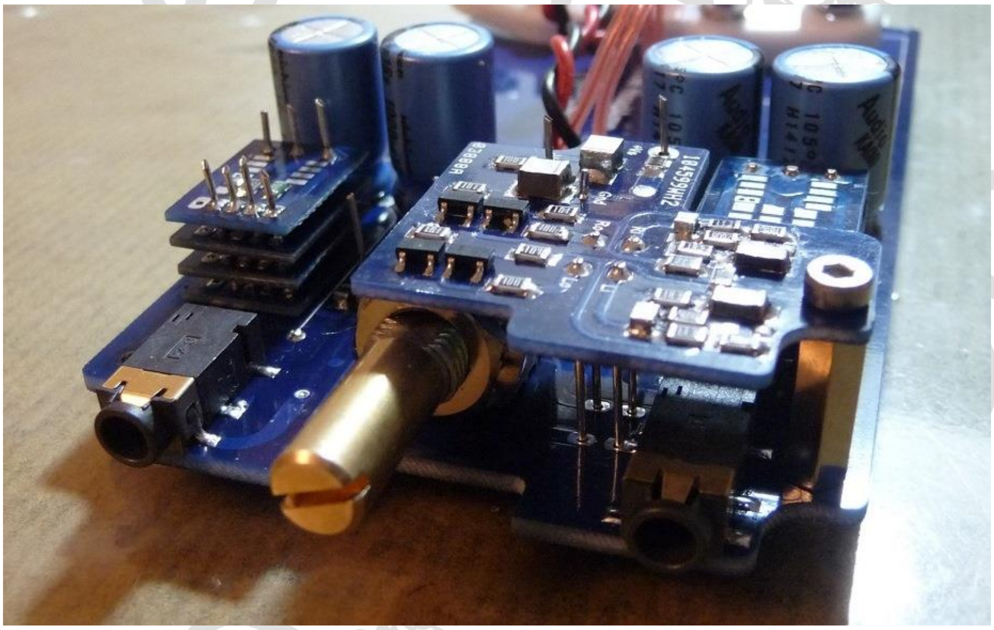
PCB Layout

Since I am not building a commercial product, I do not need to compromise electronic layout for user friendliness. I also do not want to carry unnecessary weight. That means an external charger, and all power related circuits (including power switch) are moved to the back, away from the signal handling circuits. Two 4-pole 3.5mm gold-plated phone jack sockets are used for both input and output. This allows separate power ground tracks at the output and true 4-wire connections to the headphone. At the input side, however, the 2 ground connections are soldered to a common ground plane on the PCB. This is necessary because the Cross Feed circuit has to use a common ground for both channels.

As I am using 4x BUF634 in parallel myself, I need to stack them to the same foot print as the DDPAK device on the PCB. So I choose to use SOIC8 package and have an adaptor board which emulates the same connections as the DDPAK, with 5 pins on one end and a thermal connection to –Vs on the other. Extra holes are provided for to allow connection wires to be directly soldered between the stacker boards and the main board. The adaptor board has large insulated copper pads above and below the SOIC package. A thin layer of thermal compound on both top and bottom of the package will allow good heat transfer to the thermal pads. For the uppermost BUF, an empty board is used to provide for heat dissipation from the top of the SOIC.

Extra connections are provided for on the main board to allow for the cross feed filter buffer board. When not used, one can simply bypass the connections with two short jumpers.

The servo is optional and is therefore designed as a daughter board which is placed directly over the AD844. At that location, it can be conveniently connected to Gnd, both power supply rails, as well as the Tz pin. It then only requires a single wire from the output of the buffer.



Thermal Management

The total current consumption for each channel is around 40mA, That means total dissipation for stereo is 1.4W, of which 0.9W comes from the buffer IC's. Since the PCB foot print below the batteries are not otherwise useful, I put a large insulated pad there which is well connected to the negative rail. The latter is also use in the DDPAK package for thermal dissipation. This large thermal pad then matches an elevated aluminium surface (a 2.5mm aluminium plate bolted to the bottom of the PCB, or even a thermal gap pad now available widely) through which heat is conducted to the case for dissipation. There are plenty of contact area for little heat, so normal thermal grease would be fine when used in combination with an aluminium plate.

Each of the 8x SOIC8 buffer IC's only dissipates 0.1W. As already mentioned, they are sandwiched between large copper areas on the adaptor PCB for heat transfer. The stack has 3x 0.8mm copper pillars (equivalent to a 43mm wide track on the PCB) for heat conduction to corresponding holes on the PCB where the DDPAK thermal pads are also located. If cost is no issue, Arctic Silver Ceramic thermal grease could be use on both top & bottom of the SOIC's.

Simple Charger

We have published before a simple charger circuit for NiMH batteries, then used for the SEN IV Converter. In case of a 8,4V nominal NiMH of 300mAh, one need simply a regulated supply of 9.6V in series with a 33R 1W resistor in series. For 500mAh, the voltage remains, but the resistor should be 20R. It is a good idea to charger the two batteries separately, which means a +/-9.6V regulated supply with 2x series resistors. I personally use a simple 9Vrms AC wall plug and half bridge rectification, followed by LM2941 / 2991 LDO's, and then the series resistors. Just standard datasheet circuit. Or you can simply use a suitable commercial charger.

Alternative Components

A couple of components are either difficult to get or costly. So here are a couple of alternatives. They will, however, always come with a performance penalty.

The Vishay Sfernice P9 10k stereo log pot is not widely available. But the ALPS RK097 is size compatible, except that it is of carbon film. If you wish to use the ALPS, then we recommend you take up the "50k linear pot with parallel resistor" option and use a 5.6k Susumu 0805 thin film in parallel.

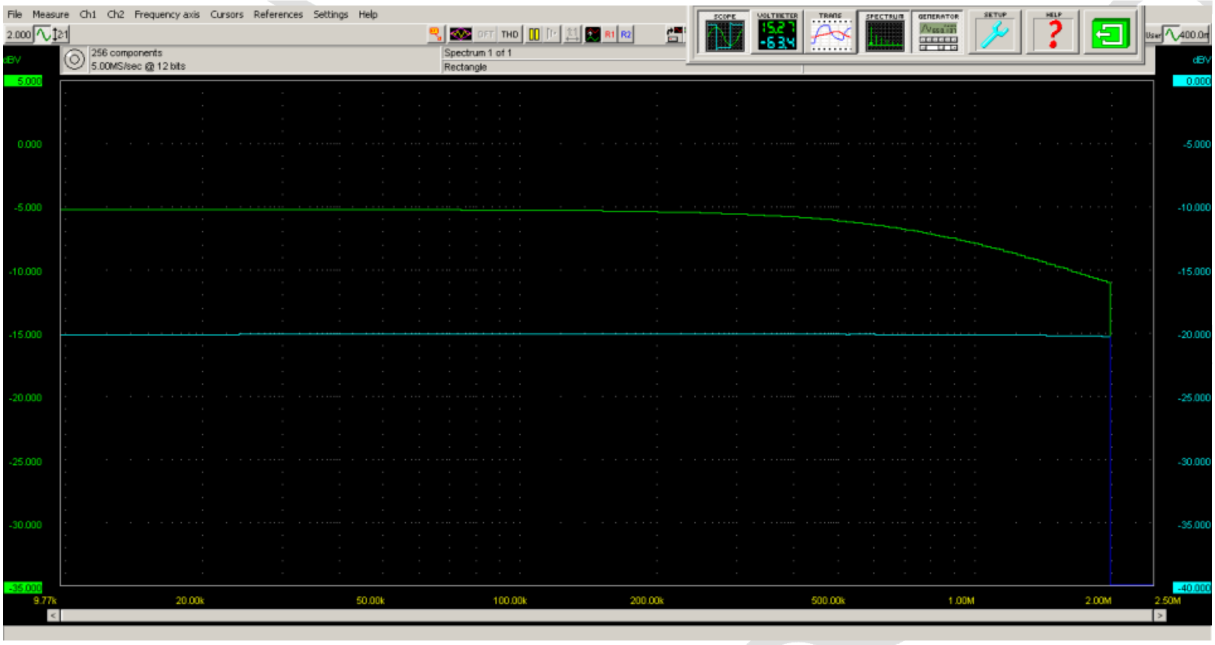
You can also find in Appendix 1 a comparison of currently available buffer IC's on the market. If you have a high impedance and/or sensitive phone and are not chasing THD figures, then a single LME49600 or LMH6321 in DDPAK package would be a good alternative. The LME49600 is however at end of life and will disappear soon. The LMH6321 actually has lower offset, so you might be able to do away with the servo and just use a R trim. It does have a much lower Zin, so you should drive it from pin 6 of the AD844. It is also the only one of the lot that has clear THD performance information in open loop in the datasheet. The other penalty is of course that it has 7 pins instead of 5,But you can twist some pins round to suit the BUF634 layout.

Although you only need 4x 2SK209GR with matched Idss, my experience is that you should buy at least 20 to match, if you want low DC offsets. You can of course also use any pin compatible N-JFET in SOT23 with about 3mA Idss, such as LSK170A, 2SK3666-3, 2SK208-GR…..

Measured Performance

As expected, the amp is very fast with -3dB bandwidth at 1MHz. 100kHz square wave is nice with no overshoot. And the sound ? Very seductive. I cannot stop listening ……

(Green is output, cyan is input)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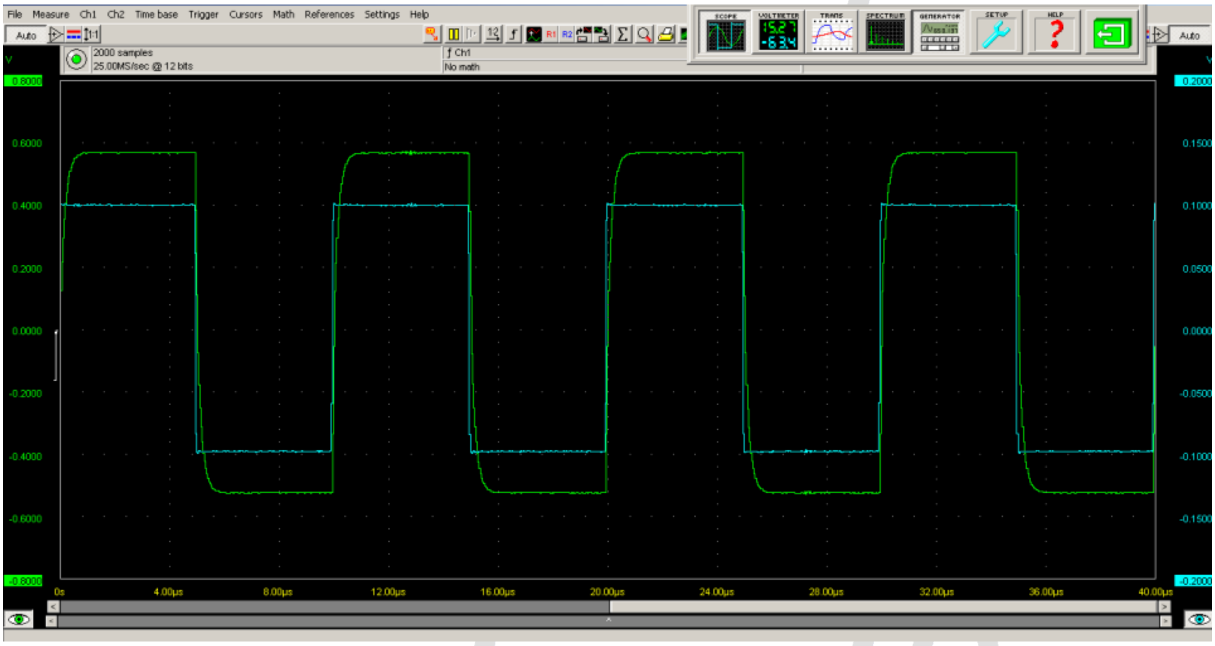
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Appendix 1 Comparison of Buffer IC's

		BUF634	OPA633	LME49600	HA5002	LT1010	LMH6321
Vos	± mV typ.	30	5	17	5	150	4
Z_in	ohm	80M / 8M	1.5M	7.5M / 5.5M	3M	--	250k
C_in	pF	8	1.6	--	--	--	3.5
I_in	± µA	2 / 20	20	1 / 3	2	250	2
I_q	mA	1.5 / 15	25	7.3 / 13.2	8.3	9	11 / 15
Z_out	ohm	7.4	5	5	3	7.5	5
Noise	nV/sqrt Hz	4	--	2.6	--	25	2.8
Vs	± V	18	20	20	22	22	16
Package		DIP8, SOIC8, DDPak5, TO220	DIP8	DDPak5	SOIC8	DFN8, DIP8, TO220	SOIC8, DDPak7
Price	Mouser USD	9.45	12.37	6.37	9.80	4.82	4.98

Appendix 2 Recommended Bill of Material

Qty	Component	Mouser
Portable Amplifier Stereo		
2	AD844AN	584-AD844ANZ
2	OPA140AIDBVR	595-OPA140AIDBVR
8	BUF634U matched Vos	595-BUF634U
8	Susumu 0805 1R 1%	754-RL1220S-1R0-F
8	Susumu 0805 0.5% 10R	754-RR1220Q-100D
10	Susumu 0805 0.5% 10R	754-RR1220Q-100D
10	Susumu 0805 0.5% 3.9k	754-RR1220P-392D
10	Susumu 0805 0.5% 22k	754-RR1220P-223D
10	Susumu 0805 0.5% 200k	754-RR1220P-204D
10	Susumu 0805 0.5% 1M	754-RR1220P-105D
1	Vishay P9A2R100FISX1103ML	Farnell 8791384
8	Panasonic ECPU1C104MA5	667-ECP-U1C104MA5
2	Panasonic ECPU1C684MA5	667-ECP-U1C684MA5
4	Nichicon KA 1000µF 16V	647-UKA1C102MPD
1	APEM 25446NAH	642-25446NAH
2	9V Battery Clip	
2	9V NiMH Batteries	
1	Hammond 1550B Modified	546-1550B
1	XEN ZGF Portable PCB + Cross Feed	
8	XEN BUF634 Stacker PCB	
2	TSH-3896D 3.5mm Jack	
Cross Feed Buffer Option		
4	Susumu 0805 0.5% 10R	754-RR1220Q-100D
4	Susumu 0805 0.5% 100R	754-RR1220P-101D
2	Susumu 0805 0.5% 5.49k	754-RR1220P-5491D-M
2	Susumu 0805 0.5% 11k	754-RR1220P-113D
2	Susumu 0805 0.5% 18k	754-RR1220P-183D
2	Susumu 0805 0.5% 27k	754-RR1220P-273D
2	Susumu 0805 0.5% 90.9k	754-RR1220P-9092D-M
4	2SK209GR matched Idss	757-2SK209GRTE85LF
2	Panasonic PPS 0805 2,2n	667-ECH-U1H222GX5
2	Panasonic PPS 1206 22n	667-ECH-U1C223GX5
2	Panasonic ECPU1C105MA5	667-ECP-U1C105MA5

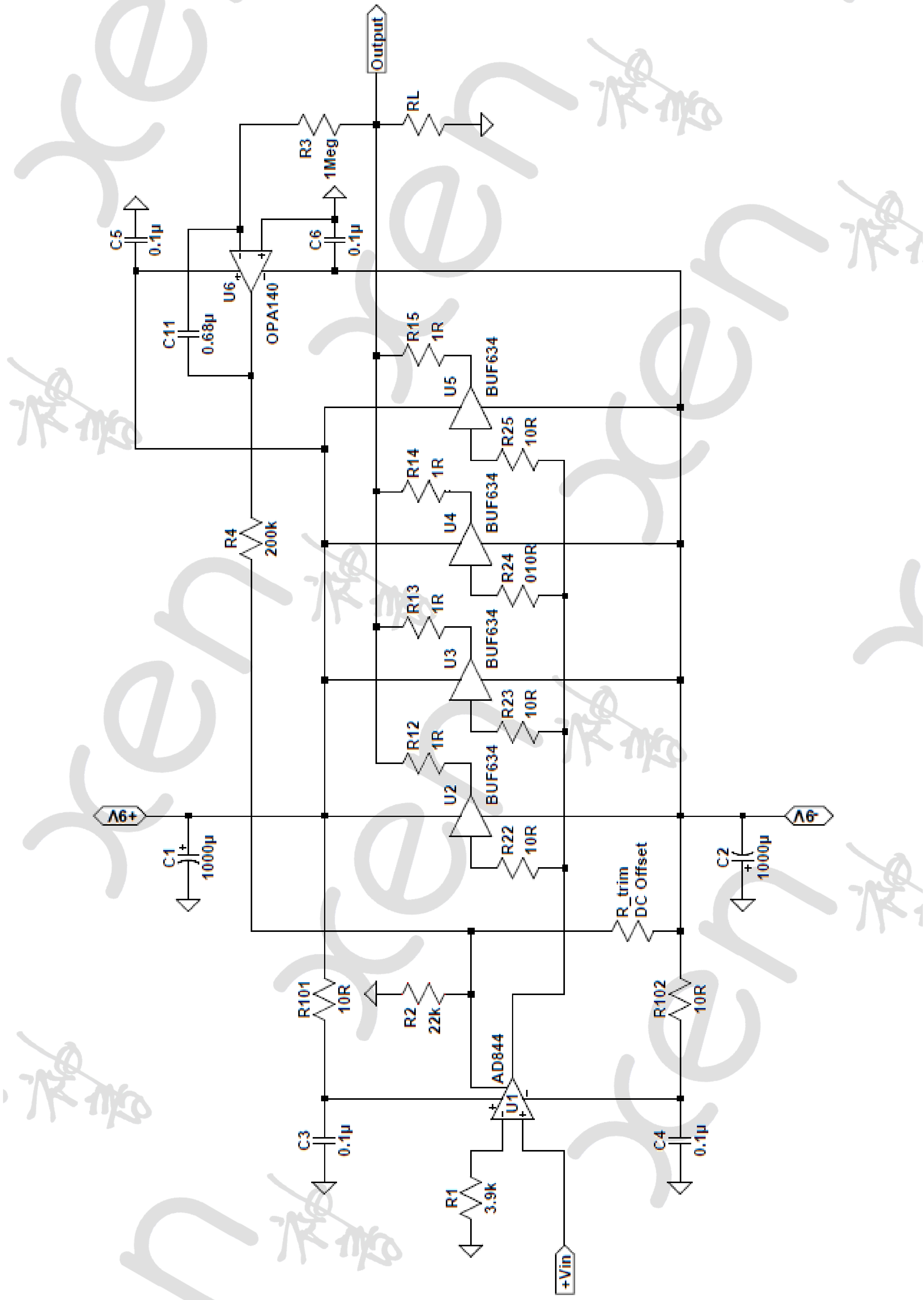

Figure 1 **ZGF Portable Schematics V3**
(using 4x BUF634U in parallel)