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A Phono PrePreamp for the (SA) CD Age, Part 3

By Norm Thagard

In the final part of this series, the author resolves some critical power-supply requirements.

This design does not offer exceptional power-supply rejection. Therefore, it requires a good power supply to realize its potential. For this reason, in addition to the usual full-wave rectifier/capacitor-input filter, there is an additional RC filter section and shunt voltage regulator for each supply. In order to physically separate the power transformer from the preamplifier circuitry, the power supply is partitioned into a raw supply contained within its own enclosure and voltage regulators located within the preamplifier enclosure. This technique is frequently used with sensitive preamplifiers.

POWER-SUPPLY SETUP

All components through the RC filter stage are located within the raw supply enclosure (**Fig. 5**). The remaining circuitry of the four voltage regulators was constructed on a single board physically located within the preamplifier enclosure. The regulator circuitry is shown in **Fig. 6**.

The two enclosures are connected with approximately 3′ of cabling suitable for conducting DC current in excess of 150mA, which is the approximate preamplifier current draw per channel from the positive power supply. The per-channel draw from the negative supply is about 50mA. Due to additional current drawn by the shunt voltage regulators, 18-gauge stranded wire is recommended for the interconnections.

The transformer is common to both channels, but from that point separate components are required for right and left channels. Only one channel is completely depicted.

The shunt regulators are based upon a design found on the Internet[25]. In reviewing back issues recently, I discovered that the design is similar to one that appeared in *TAA* a number of years ago[26]. While simple, their performance is excellent, far exceeding that possible with the standard IC regulators widely available. The published design is slightly modified by replacing the BJT shunt element with a MOSFET and sourcing collector current for Q_{101} and Q_{102} directly from the regulated bus rather than the well-filtered but nonetheless unregulated source from the raw power supply.

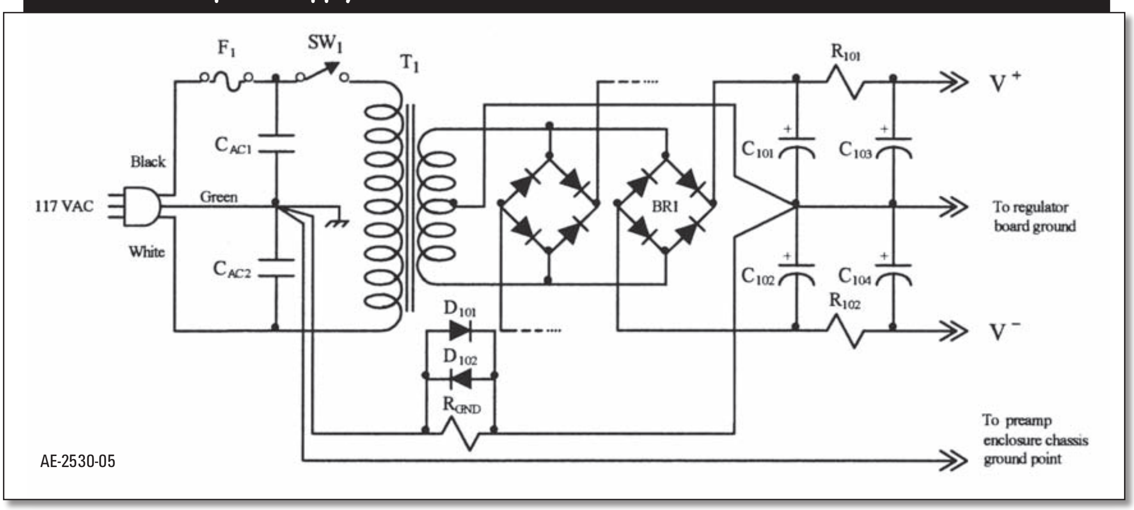
Initially, I used medium-power Darlington transistors in lieu of M_{101} and M_{102} in order to obtain sufficient voltage drop across R_{109} and R_{110} to keep those resistors at 1.8kΩ while still providing adequate collector current for Q_{101} and Q_{102}. Per a suggestion by Brad Wood, who also kindly proofed this article and offered several useful suggestions for its improvement, I replaced the Darlington transistors with MOSFETs. The gate-source voltages of the MOSFETs are even higher than the Darlington base-emitter voltage, which results in higher stage gain and consequently a greater level of negative feedback. He also recommended placement of C_{107} and C_{108} for stability reasons.

REGULATION OPERATION

I suspect that just about any medium-power MOSFETs will work. If dissipation can be limited to less than 1W, then you can substitute even low-power MOSFETs. As in the first stage of the preamplifier, I chose Q_{101} and Q_{102} for their noise performance. Substituting 2N4401 and/or 2N4403 types should give similar results.

At DC, these are essentially zener diode-based shunt regulators. For the

FIGURE 5: Raw power supply.



positive regulator:

$$V_{reg}^{+} = V_{BE-Q_{101}} + V_{Z_{101}} + V_{R_{105}}.$$

Regulation is degraded by the presence of R_{105}, but its inclusion greatly reduces the effect of zener diode noise. The value chosen is a reasonable compromise between the two antagonistic requirements. If some trimming of regulated positive or negative rail voltage is desired, it can be raised by increasing R_{105} or R_{106}, respectively, and lowered by a decrease in the values of those resistors. The values used in the prototypes yielded rail voltages of about 17.5V.

Zener currents are set, ignoring the small error due to base current, by R_{107} and R_{108} according to:

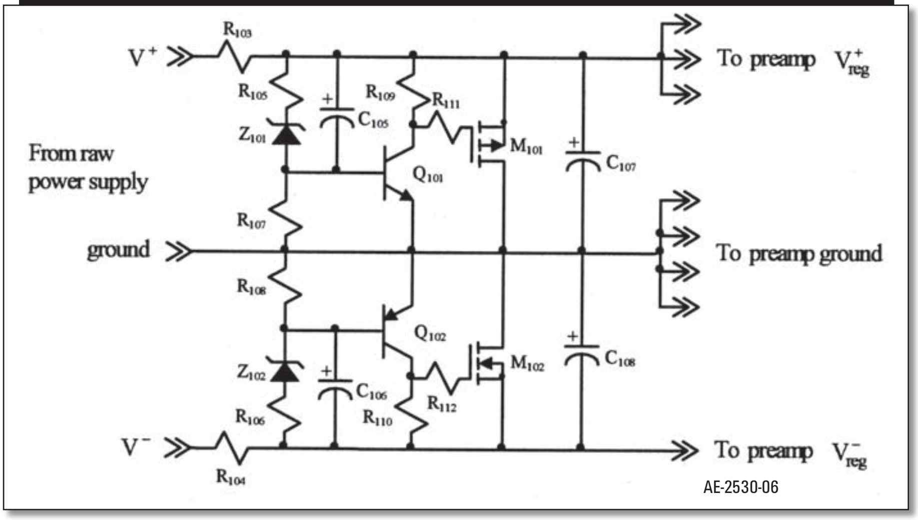
$$I_Z = \frac{V_{BE-Q_{101}}}{R_{107}} \cong \frac{V_{BE-Q_{102}}}{R_{108}} \cong \frac{0.7}{100} = 7 \text{ mA}.$$

This value was chosen because it is close to the nominal current on which 1N5246B zener diode specifications are based. For example, dynamic resistance is guaranteed to be no more than 17Ω at I_Z = 7.8mA[27].

$Q_{101}M_{101}$ and $Q_{102}M_{102}$ form feedback amplifiers with unity AC gain, thanks to coupling to the Q_{101} and Q_{102} bases through C_{105} and C_{106}, respectively. Open-loop gain is almost that of first-stage gain since the MOSFETs are source followers. First-stage gain on the positive regulator is shown in **Equation 1**.

The effective dynamic resistance

FIGURE 6: Voltage regulators.



Equation 1.

$$-g_{m-Q_{101}}R_{109} = -\left(I_{C-Q_{101}}/V_T\right)R_{109} = -\left[\left(V_{GS-M_{101}}/R_{109}\right)/V_T\right]R_{109} \cong -3.5\text{V}/25\text{mV} = -140 \text{ (43 dB)}$$

in shunt across the rail is greatly reduced by this feedback and the favorable $R_{dynamic}/(R_{dynamic} + R_{103})$ voltage divider ratio. This feedback is effective over the whole audio frequency band, reducing the effect of noise and to a lesser extent, ripple.

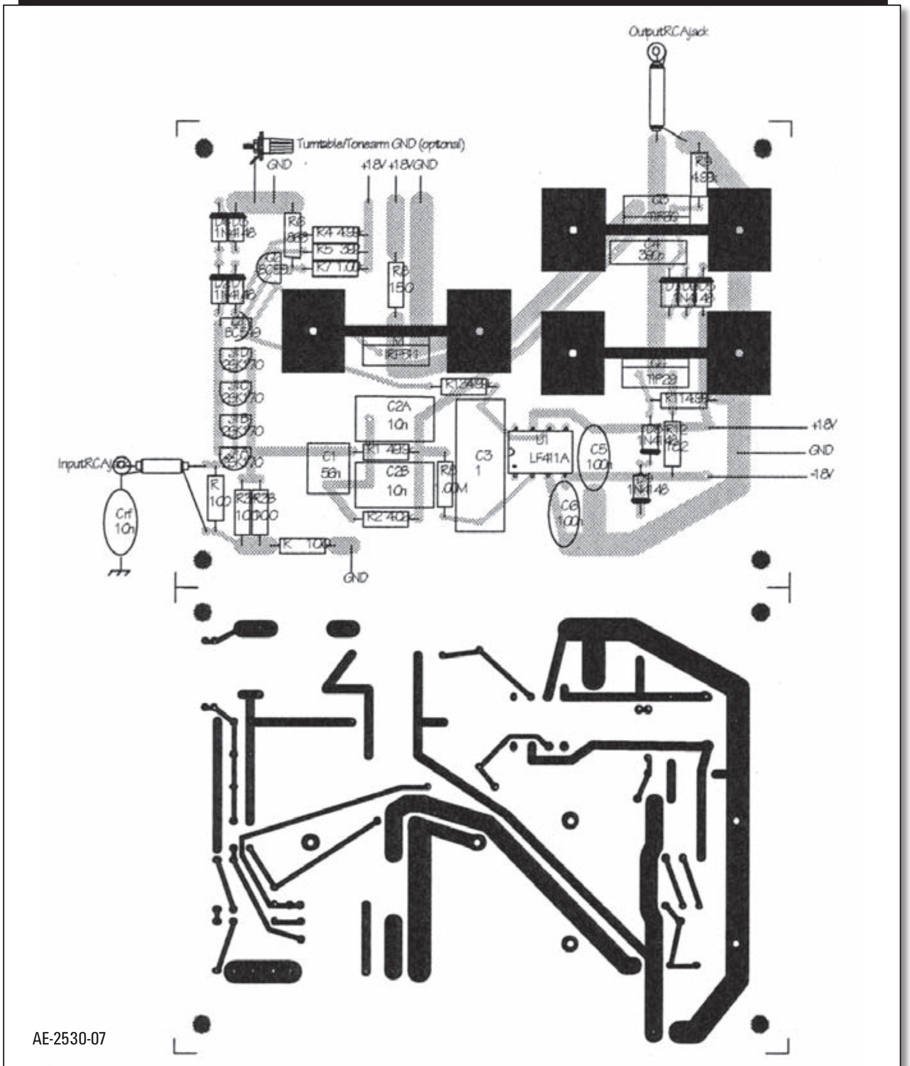
These are shunt regulators, so don't neglect series resistors R_{103} and R_{104} as I inadvertently did, forgetting the big capacitors of the RC filter back in the remotely-located raw power-supply enclosure. These resistors improve performance as their values increase. However, if they are too large, the regulator will "drop out" as voltage falls below that necessary to keep the zeners operative.

Although a power transformer with 40V CT secondary is specified, the prototype used one with 36V CT rating. While this placed the shunt regulators rather close to drop out, reducing R_{101} and R_{103} to 22Ω and R_{10} and R_{104} to 62Ω did allow proper regulator operation. Although power wastage is ecologically unsound, higher secondary voltages allow increased resistor values that improve performance.

On the other hand, lowering the values of these resistors too much can result in excessive power dissipation in the MOSFETs. I mounted the MOSFETs on small heatsinks, just in case. Fortunately, the source-follower topology places the drains at ground, so no insulation between transistor and heatsink is required even if, as was the case for the prototype, the heatsinks are grounded.

It's not a bad idea for a Variac® to be available to monitor regulator voltage while running the line voltage up to 110V RMS. The regulators should

FIGURE 7: Preamplifier board parts placement and pattern.



"kick in" below this voltage to guarantee regulation even in periods of line voltage drops. If the regulators kick in at voltages substantially less than, say, 100V RMS, then perhaps some thought should be given to increasing the values of R_{101} – R_{104}.

STAR GROUNDING

The pattern of interconnections from the regulator board to the preamp boards is important. Improper connections, which often can work under less demanding conditions, may wreak havoc with high-gain audio circuits such as this one. The original layout used a common ground bus. There was an intermittent motorboating that was extraordinarily dependent upon physical location of the preamp enclosure. Breaking this bus and supplying four separate ground interconnections seemed to eliminate this problem.

Perhaps I should have paid more attention to the warning in one reference that read ". . . or, in audio circuits, (daisy-chaining of ground returns can cause) low-frequency "motorboating" oscillation . . . The extra investment in wiring is just about always worth it."[28] At a minimum, ground returns should be separate for the first and second stages. For what it's worth, the use of R_{iso} seemed to make the preamp less sensitive to grounding variations.

The same reference also notes that "The rule also applies to the power rail feed as well as to its return, and, in fact, to any connection where current is being shared between several circuits[29]." For this reason, three separate interconnections were used for the positive rail. The negative rail required only a single connection to the regulator board because that power is only supplied to the op amp and the output (second) preamp stage.

I have read that a ground "mecca" typical of the star grounding technique is just a crutch whose necessity is readily obviated if proper attention is paid to the problem[30]. I am sure that application of the technique can be overzealous, but use of separate power and return leads is sometimes essential. Anything that reduces IR voltage drops on the buses will help. Keeping wiring inductance low also helps. Broad buses and large diameter wires reduce *IR* drops and, to some extent, inductance. The best technique for reducing inductance is to shorten traces and wires.

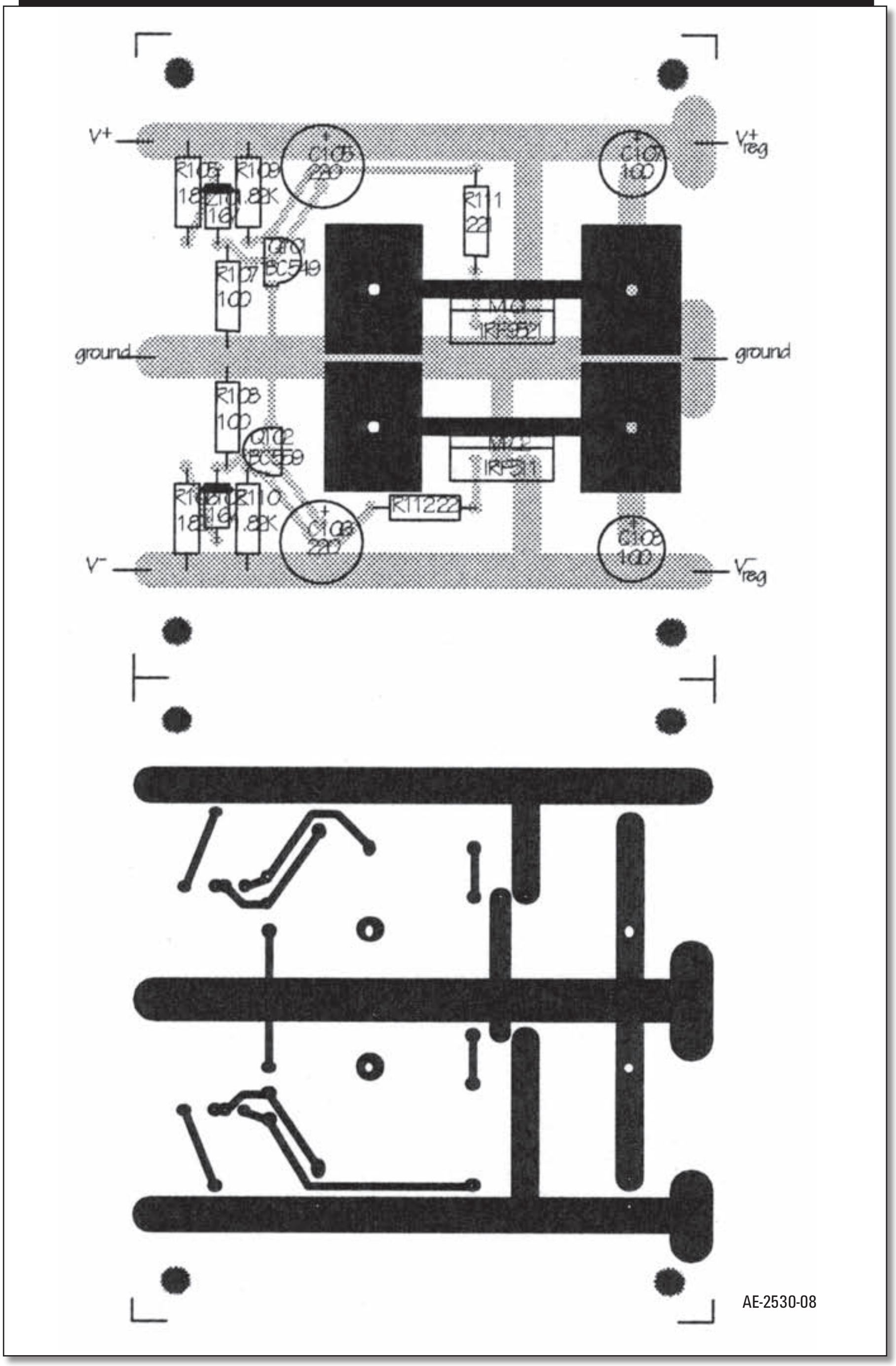
In the breadboard step of the design process, the input stage was initially supplied through an additional zener-based shunt regulator. This is a good way to avoid interstage coupling via the power supply if you attend to the zener noise. A simple additional RC filter between the output stage supply and the first stage power bus may be similarly efficacious.

Despite this discussion, the actual culprit proved to be capacitive coupling to the very sensitive circuitry with its low-frequency gain of 10,000. Grounding the preamp enclosure to the power-supply enclosure and hence the power-line ground did not fully protect against this coupling. However, connecting one of the right-channel PC-board grounds to preamp enclosure ground at the binding post as shown in **Fig. 7** completely eliminated the low-frequency oscillations. The binding post was grounded to the preamplifier chassis to allow for an optional grounding connection from the tonearm or turntable. With this ground connection in place, the power-supply enclosure should *not* then be connected to the preamp enclosure, as this will result in a ground loop and audible hum.

A simpler power-supply and ground interconnection scheme between regulator board and preamp boards might, in fact, work. However, after the modification, I was unwilling to return to the original common bus configuration.

Please refer to **Figs. 7** and **8** for the details of the interconnections between preamp and regulator boards. The prototype circuitry was placed on prototyping boards rather than the PC board patterns shown. I found no errors in proofing the board designs, and the PC patterns generally follow the layout of the prototyping boards. Even so, you should confirm that there are no errors in the patterns as published,

FIGURE 8: Regulator board parts placement and pattern.



because an important verification step is missing.

Although I originally employed a grounding scheme identical to that of my previous phono preamp, there was an audible hum unless a three-wire-to-two-wire AC plug adapter was put in place. Isolating the circuit ground from chassis and power line grounds with 10Ω resistor R_{GND} eliminated the hum and the need for the adapter by reducing ground loop current. I have used this technique to eliminate ground loops at the inputs to my amplifier designs, and some commercial preamps use this scheme as well. The resistor is subject to failure due to potential differences between circuit and power-line ground. Back-to-back diodes D_{101} and D_{102} protect R_{GND} and provide mutual self-protection against voltages that would exceed their peak inverse voltage (p.i.v.) rating by clamping resistor voltage to one diode drop.

Be especially careful that the RCA input and output phono jacks are isolated from the chassis. I found that the RCA input jack of the right channel was contacting the chassis. Although initial continuity checks indicated no problems, after a number of insertions and removals of interconnects into the jack, the motion caused a metal washer on the jack to break through a mica insulator and contact the enclosure at the mounting site. The result was a large hum caused by the ground-loop that was produced.

Do not despair, however, because I overcame these problems. If you follow the bus suggestions and use components and values specified in the parts list, you should have no problems with the power supplies.

MEASUREMENTS

The preamplifier is objectively a reasonable performer. I've previously discussed noise measurement results. THD is just 0.004% at 1kHz, rising to 0.014% at 20kHz. Both figures are taken at 10V RMS output into a 10kΩ resistive load. THD at 20Hz was less than 0.04%. Higher distortion at 20Hz was not unexpected due to the lower feedback at low frequencies.

In all cases, distortion did not increase appreciably until output voltage increased above 12V RMS. Above this voltage, noticeable "graceful" clipping became evident. Asymmetrical overload signals will upset the DC servo, but it is highly unlikely that you will encounter such inputs unless the MC version is used with a very high output MM cartridge.

RIAA tracking errors were no more than 0.1dB. I did not use a reverse RIAA network; rather, I measured output at 24 discrete frequencies from 20Hz to 20kHz[31]. The technique was to begin at 20Hz with the input amplitude that produced 10V RMS output and then measure output at various frequencies up to 1kHz with the same input amplitude. Because my distortion analyzer does not work with inputs less than 100mV, I then input a 1kHz signal whose amplitude yielded 10V RMS output and repeated the process at various frequencies up to 20kHz.

This is time-consuming and does not measure errors at all frequencies. It has the advantage of avoiding measurement error due to tracking errors in the reverse RIAA network, itself. It would be unlikely, given the close spacing of the measurement frequencies, to have tracking errors significantly greater than would those seen at the discrete measurement points.

CONCLUSION

There is not much left to explain. It was necessary to add C_4 to suppress a high-frequency oscillation. The value chosen was empirically determined as optimal from the standpoint of providing the necessary compensation while having immeasurable effect at the upper end of the 20–20kHz audio band.

Capacitors C_5 and C_6 are disc ceramic capacitors designed to suppress potential oscillation in the LF411 op amps. These were placed per National Semiconductor's recommendation[32]. In parallel with the ceramics, some would add small tantalum capacitors in the range 2.2–10μF. I did not use these in this design because I have had too many bad experiences with tantalum capacitors.

This preamplifier is essentially composed of two compound stages, to wit, two cascodes, which was also the case for my earlier design in *audioXpress*. However, the topology differs in the way these two stages are connected. In the earlier article, they were cascaded independent gain blocks. Here they are cascaded, but then both are included in a frequency-dependent feedback loop that implements RIAA equalization.

You could achieve further improvement in mid- and high-frequency noise performance by reducing the value of R_3. This would probably cause slew-rate limiting at high-frequency, high-output levels. Increasing second-stage bias currents could eliminate this problem. Improvement in low-frequency noise performance would require different transistors. Switching to BJTs would offer the most likely improvement, but I have noted the interfacing problem with BJT inputs.

For those with a MOSFET fetish, a version replacing Q_3 with a p–channel MOSFET worked fine in PSpice simulation. The substitution did require a current source in lieu of R_8, but neither noise performance nor distortion suffered from the modification. However, I was satisfied with performance of the design shown here, and there is a philosophical argument that better is the enemy of good.

SOUND IMPRESSIONS

I should mention that I embarked on this project as a way to drive my power amplifiers directly from the output of this phono preamplifier, bypassing the system preamplifier altogether. These amplifiers require only 1.5V RMS input for 480W output. Thus, I could easily reduce R_3 for further noise reduction because onset of slew-rate limiting would not occur at a level these amplifiers would ever see. The point is, along the way I modified the design to be more generally useful, in the process sacrificing some advantages specific to my use.

Some strongly opinionated people notwithstanding, there are arguments for and against any scheme. I prefer the topology of the earlier design because gain can be increased or decreased by a change in the value of a single resistor in the second stage. With the earlier design, I increased overall gain and altered the gain distribution between the two stages allowing the phono preamplifier to drive the power amplifiers directly. The sound was, to my ear, noticeably cleaner. In any event, there is no way that passing the phono pre-preamp signal through the two additional amplifier stages of the system preamp can improve the sound.

For those who built or contemplate building the original design, I feel even better about its performance after several years. Although not designed for them, it performs respectably with both low output moving-magnet and moving-coil cartridges. It was not optimized for noise, yet noise was low enough to be inaudible at the listening position.

The sound was gorgeous, better than I had previously ever heard from vinyl. There was no volume control because the unattenuated gain was just sufficient to drive the speakers to a comfortable level provided the recording level was medium to high. Those records in my collection with low recording levels did not yield a high enough (to me) volume.

The major advantages to the new design are better noise performance, higher closed-loop gain, and, in my humble opinion, better sound. With a system in which the amplifiers are driven differentially via a phase splitter, the higher gain necessitated modifying the phase splitter to allow insertion of a 10kΩ dual potentiometer at its input for use as a volume control. For those who may have constructed the phase splitter[33], I will mention that the modification was to replace the BJT with a MOSFET as described in the referenced article.

As of this writing, the preamp has been in my system for over a year. Given how many times I have mounted and dismounted the preamp boards from the chassis and the number of times I've placed voltmeter and oscilloscope probes on the boards with the

POWER SUPPLY

Resistors *are 1%, metal film, 0.25W resistors unless otherwise specified. Values are in ohms.*
R_{GND} – 10, 2W metal film
R_{101}, R_{103} – 25, 3W wire-wound or metal film
R_{102}, R_{104} – 75, 1W wire-wound or metal film
R_{105}, R_{106} – 182
R_{107}, R_{108} – 100
R_{109}, R_{110} – 1.82K
R_{111}, R_{112} – 221

Capacitors *are 35V aluminum electrolytic capacitors unless otherwise specified. Values are in farads.*
C_{101}, C_{102} – 4.7m (1mF = 1×10^{-3}F)
C_{103} – 10m
C_{104} – 4.7m
C_{105}, C_{106} – 220μ, 25V
C_{107}, C_{108} – 100μ, 25V
C_{AC1}, C_{AC2} – 10n, 1kV disc ceramic

Diodes
BR1 – 1A, 200 PIV bridge rectifier
D_{101}, D_{102} – 100 p.i.v., 3A (1N5401 or equivalent)
Z_{101}, Z_{102} – 16V, 500mW (1N5246B or equivalent)

Transistors
Q_{101} – BC 549C
Q_{102} – BC 559C
M_{101} – IRF 9521
M_{102} – IRF 511

Transformer
T_1* – Power transformer designed for operation from 120V AC, 60Hz mains. 40V CT, 1A secondary.

Fuse
F_1* – 200mA normal blow

Switch
SW1* – Mains switch, 120V AC, 5A

*Common to both channels. Only one required.

inevitable occasional slip, I believe the design to be robust and forgiving of moderate abuse. This is a not-inconsequential consideration in a DIY project.

Gain cannot be easily changed with the present design. If gain is to be changed, five component values must be recalculated and the components swapped out. Even so, I have impressed myself with this current design. I wasn't at all sure at the outset that a reasonably performing preamp for low-output phono cartridges could be produced from two gain stages. Yet noise performance, RIAA tracking, and distortion are all perfectly acceptable.

Typically, moving-coil systems implemented with just two electronic stages require a step-up transformer. The noise benefits are certainly worthwhile, but when I look at transformer specifications for distortion and frequency response, I am moved to avoid them. If these factors were not enough to preclude my use of a transformer, the price tag of a good transformer is.

I am coming to the view that the amount of ambience heard in sound reproduction is somehow a measure of overall accuracy. If that is the case, this MC phono preamp is exquisitely accurate. Reproduction of big band and rock music is attention-getting. The most noticeable improvement, though, is in the reproduction of classical, i.e., orchestral music. Orchestral recordings have always seemed to lack something. No more is this true. There is both improved detail in the precise location of instruments and increased dynamics in, for example, the visceral impact of percussion.

As a member of the board of and season subscriber to the very good Tallahassee Symphony Orchestra, I have periodic opportunities to hear live performances. In some cases, the sound in my listening room is better than that in the concert hall, probably due to favorable positioning of the recording microphones and perhaps a better concert hall in the recorded version of a given work. This could not be the case, though, if the system were not up to the task.

No system can provide the impact of sitting on the stage during a performance of Gustav Holst's *The Planets*," which I narrated for the Chattanooga Symphony Orchestra a short time back. Nonetheless, if you place this article's preamp in a good system, I have no doubt that you will like what you hear.

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