An Ultra-Low Distortion Direct-Current Amplifier

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A high-power complementary symmetry emitter-follower output amplifier is described which can drive loads in the impedance range of 4 to 16 ohm, providing distortion of less than 0.2% in the range from 20 to 20,000 Hz. Performance measurements on the amplifier are presented and discussed.

INTRODUCTION Although NPN silicon power transistors have been used in commercial audio amplifiers for several years, it is only recently that high-power, high-beta, high-voltage, high-frequency silicon PNP transistors have been available. The commercial appearance of these devices has made possible the design of high-power complementary symmetry emitter-follower output amplifiers capable of driving loudspeakers or other loads in the impedance range from 4 to 16 ohm, with very low distortion and excellent performance up to 100,000 Hz and beyond.

CIRCUIT DESIGN

Figure 1 is a schematic diagram of the Locanthi three-stage cascaded complementary symmetry emitter-follower output circuit, hereafter referred to as the T-circuit. (Because of its NPN-PNP symmetry, the configuration has the general appearance of a bridged-T circuit.) Before describing the special advantages of this particular design, perhaps it should be explained why the complementary symmetry emitter-follower was chosen as the starting point for the development of an amplifier.

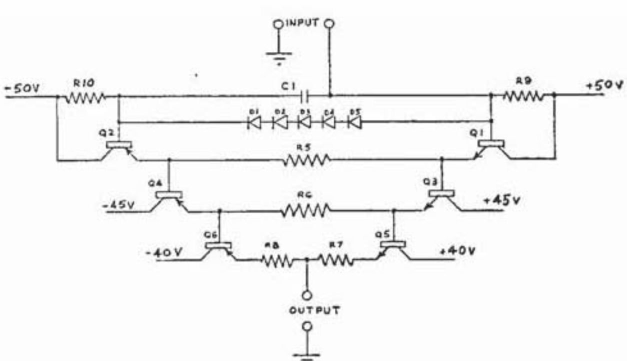

Fig. 1. Three-stage output circuit (note the **T** configuration).

First, a look at the negative side of the picture. Of all three possible configurations for a transistor output circuit, the emitter-follower places the most difficult demands upon the preceding driver stage. In the first place, since β is a function of output current, the impedance presented by the output stage to the driver varies directly with the output current. Obviously, a high-impedance driver stage cannot be used successfully because distortion will result as the β of the output stage varies.

Moreover, the base-to-emitter capacitance of most transistors is quite large, and varies with the output current of the transistor. At high frequencies, this nonlinear input capacitance presented by the emitter-follower to its driver stage results in another limitation on performance. The high-frequency distortion produced by this effect can be severe, particularly with germanium output transistors. Even though the input capacitance of silicon power transistors is an order of magnitude lower than that of comparable germanium devices, the problem is still there and cannot be ignored.

Third, the power gain of an emitter-follower is relatively low, approximately a factor of ten lower than that of either of the other two possible output circuit configurations. Fourth, since the voltage gain of the output stage is only about 0.92, the driver must supply 8% more voltage than appears across the load impedance.

These disadvantages were overbalanced by the desire for a low-distortion voltage-following amplifier of very wide bandwidth. Since the voltage gain for the output transistors is approximately equal to $\beta/(1+\beta)$, and since beta at the highest output current for the transistors selected is about 25, the instantaneous output voltage at the point of maximum output current is down only 4%;

since the maximum β is about 50, the actual total harmonic distortion, therefore, is only approximately 1.5%.

In other words, by accepting the penalties inherent in the emitter-follower, it was possible to start with a bandwidth greater than 200 kHz and a total harmonic distortion of only about 1.5%. Proceeding from this point, the cascaded three-stage T-circuit was developed to take maximum advantage of these performance capabilities.

Perhaps the most immediately apparent feature of the T-circuit is its excellent thermal stability. The output transistors (*Q5* and *Q6* in Fig. 1) are connected directly to a high current power supply of about ±40 v potential. Each base of the output circuit has a path allowing the collector-to-base leakage current to flow through its opposite driver-stage emitter. It can be seen that suitable collector-to-base leakage current paths are provided for all of the transistors.

The load impedance is amplified by a factor of about 100,000 as it is reflected back to the input of the T-circuit, and with an input driver collector load resistance of about 5,000 ohm, the DC stability factor is of the order of 20. There are no DC thermal runaway problems.

The ratio between reflected load impedance and input collector load is advantageous in another way as well. A typical 8 ohm load is reflected back to the input as about 800,000 ohm. Since *R9* is only 5,000 ohm, the resulting 160:1 ratio swamps out any effects back by the beta nonlinearities of *Q5* and *Q6*.

A single bias supply consisting of diodes *D1* through *D5* provides the necessary forward bias for the three cascaded emitter-followers. The bias supply operates at a low current level and dissipates very little signal power. The operating point of each emitter-follower pair can be adjusted independently by adjusting the values of resistors *R5* through *R8*.

In practice, the transistors are biased so that with no signal they all draw a small amount of idling current. A positive signal from the input stage causes the output transistor *Q5* to conduct as necessary to deliver power to the load, and *Q6* is driven to cutoff. Since half of the T-circuit is essentially cut off when the other half is conducting, it is, in a sense, a Class B amplifier. But because we can adjust the no-signal "on" currents for each of the pair-stages independently, any crossover problems can be avoided.

Each of the driver stages has a lower beta cutoff frequency than the preceding one, so that the overall frequency limitation of the basic T-circuit is determined almost entirely by *Q5* and *Q6*. In practice, the bandwidth of the overall T-circuit is greater than 100 kHz. This gives more than two octaves above and below the audible frequency range of 20 to 20,000 Hz; thus, the classic textbook rules regarding reduction of distortion and noise with negative feedback apply. A feedback factor of 50 reduces the distortion of the output circuit alone by that factor. This is true for frequencies up to 20 kHz and essentially down to DC.

In commercial versions of this design, the output transistors *Q5* and *Q6* have a very high DC power dissipation capability as compared to that normally found in transistorized audio amplifiers. The transistors used are rated for DC dissipation of 150 watts each, so that there is no need for exotic high-speed electronic current limiting devices. All that is required is a simple thermal breaker that will open in one to sixty seconds. This is fast enough to protect the amplifier in the event of a shortcircuit at the output terminals.

It should be noted that it is necessary (one disadvantage of the T-circuit) to provide successively higher collector supply voltages going backward from the output transistors to take care of the saturation voltage drops of the preceding drivers. Supply for *Q5* and *Q6* is roughly ± 40 v, for *Q3* and *Q4* ± 45 v, for *Q1* and *Q2* ± 50 v.

Figure 2 shows the complete amplifier (one stereo channel) and the low-level driving stage. The latter is a two-stage differential DC amplifier having a voltage gain of 1200. The frequency response of the driving stage is far greater than 100 kHz, so that the single factor limiting the frequency response of the complete amplifier is still *Q5* and *Q6*. The closed loop gain of the complete amplifier is essentially *R11/R1*, or approximately 25. The feedback factor, therefore, is about 50.

MEASURED PERFORMANCE

The performance of the basic T-circuit only, without feedback, is represented in Fig. 3. This indicates total

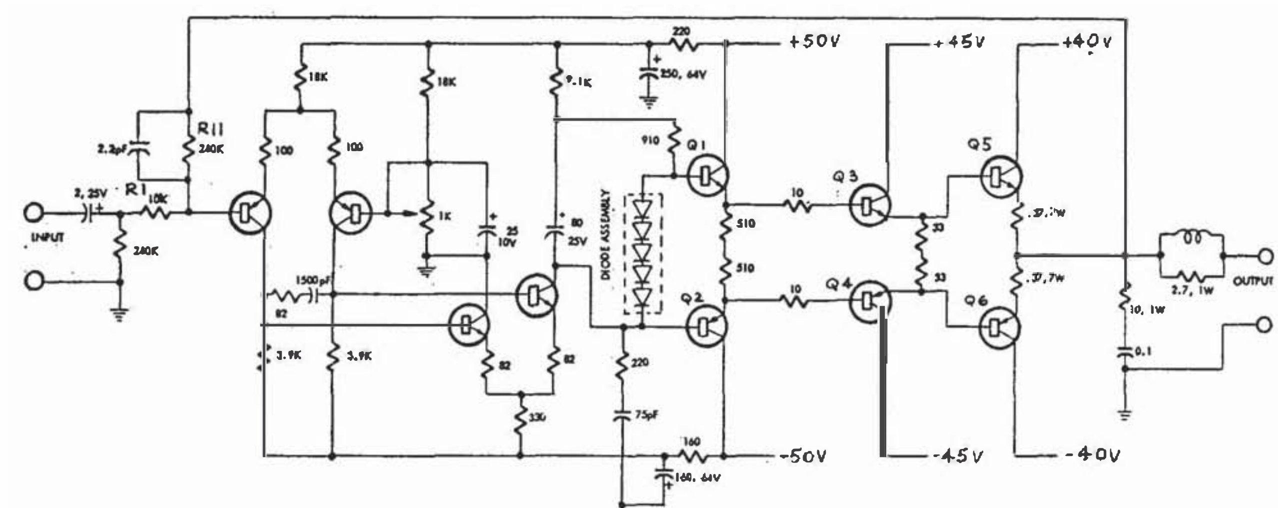

Fig. 2. Circuit of one channel of the complete amplifier.

harmonic distortion as a function of power output into an 8-ohm load for frequencies of 20, 1,000, and 20,000 Hz. At very low levels, the distortion becomes constant at about 0.25% and then increases to about 2.5% at

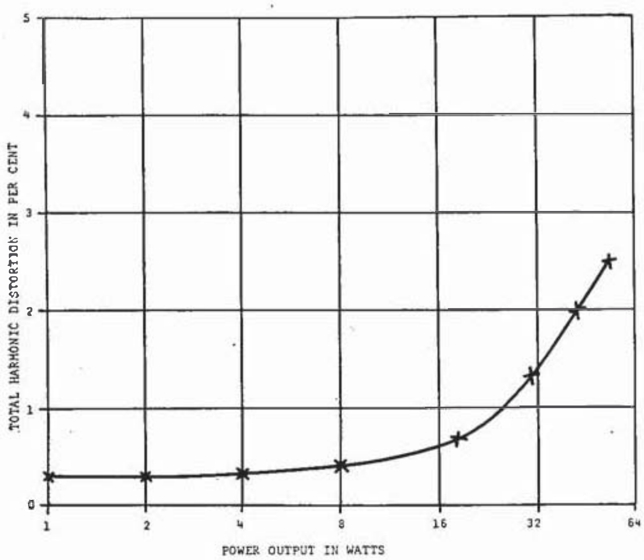

Fig. 3. Total harmonic distortion of the T-circuit without feedback. Measurements at 20, 1,000 and 20,000 Hz are essentially equal.

50 w. This by itself may not seem particularly impressive, but with a wide power bandwidth a great deal can be done with negative feedback.

Figure 4 shows intermodulation distortion as a function of power output up to 50 w equivalent sinewave power, measured with 60 and 7,000 Hz mixed 4:1. The source impedance was zero ohm and the load was 8 ohm.

Figure 5 indicates frequency response at one w and

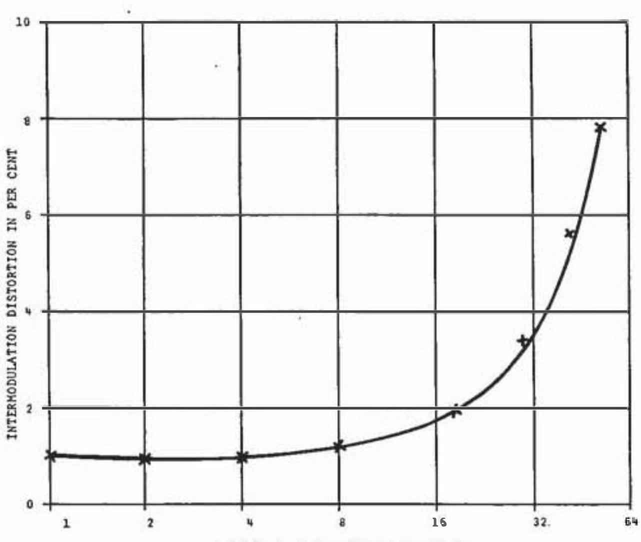

Fig. 4. Intermodulation distortion of the T-circuit without feedback, 60 and 7,000 Hz 4:1, 8 ohm load, 0 ohm source.

at 40 w into 8 ohm. Note that while the response at higher power levels is somewhat degraded, it is not more than 3 dB down at 120 kHz. (Again, Figs. 3, 4 and 5 refer to the T-circuit only, without feedback.)

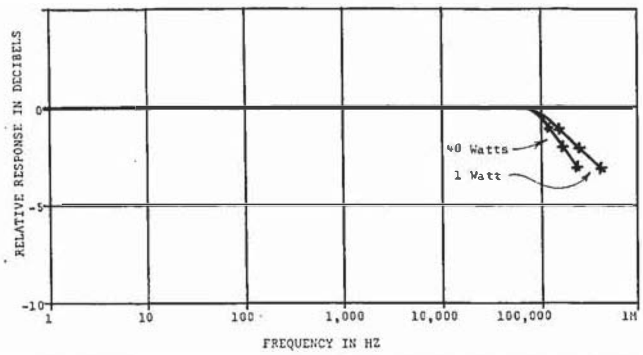

Fig. 5. Frequency response of the T-circuit without feedback, 8 ohm load, 0 ohm source.

Figure 6 shows the performance of the complete amplifier when the differential DC driver amplifier is added to the T-circuit, still without fecdback. Notice that distortion at 50 w for both 20 Hz and 1,000 Hz is less than 1%, rising only to about 1.5

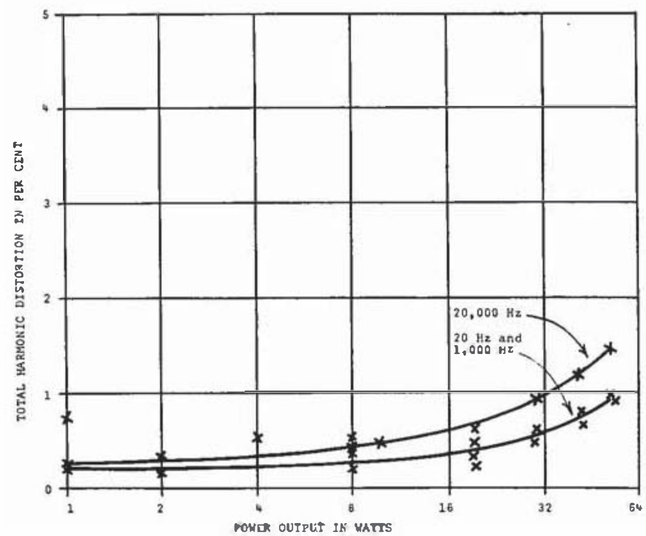

Fig. 6. Total harmonic distortion of the complete power amplifier without feedback, 8 ohm load.

distortion is lower than that of the basic T-circuit alone, presumably mainly because the T-circuit is now being driven with a partial current generator; it is possible that distortions of individual stages are slightly complementary as well. In any case, the distortion of the complete amplifier is nearly a factor of two *less* than that of the output circuit alone.

Figure 7 shows intermodulation distortion *vs* power output for the complete amplifier, still without feedback. At 50 w, IM distortion is only about 3%.

A consideration of how these measurements are affected by the inclusion of negative feedback involves one difficulty: the measured data approaches the limitations of the test instruments used, and results are therefore ambiguous at best.

To get the highest accuracy possible, an English-made Radford low-distortion oscillator was used which has less than 0.01% harmonic distortion at 20 kHz. The distortion analyzer used was a Hewlett Packard 333A which has a residual of the order of 0.01%.

Even with this equipment, distortion figures are only accurate to about ± 0.02%. For example, IM distortion

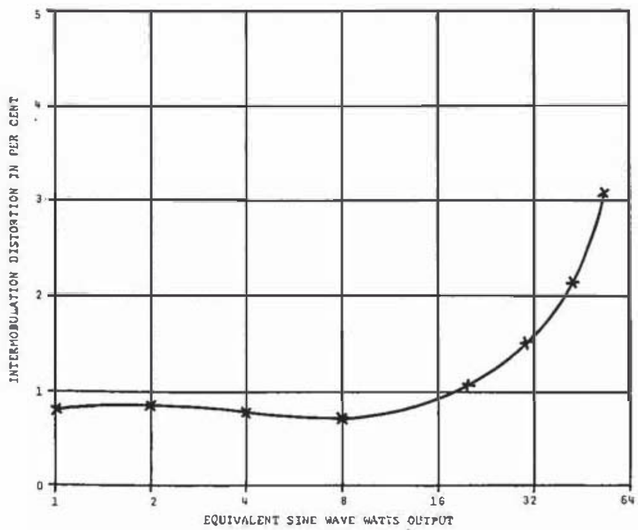

Fig. 7. Intermodulation distortion of the complete power amplifier without feedback, 60 and 7,000 Hz 4:1, 8 ohm load.

figures would be expected to be about three times greater than harmonic distortion measurements. Since the measured IM distortion values are nearly the same as the indicated harmonic distortion, it is likely that figures listed for harmonic distortion really represent the test equipment rather than the amplifier.

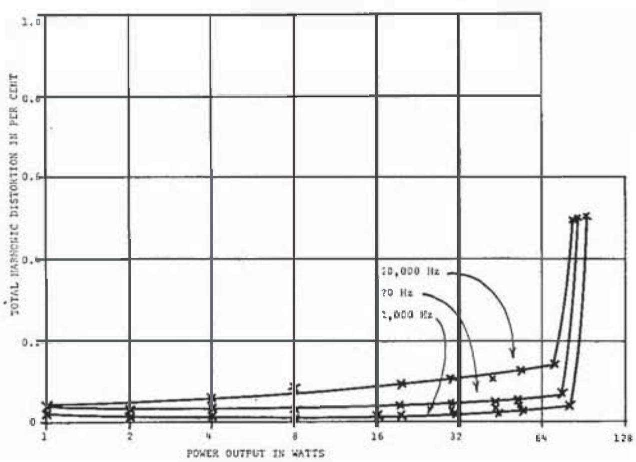

Fig. 8. Total harmonic distortion of the complete power amplifier with feedback, 4 ohm load.

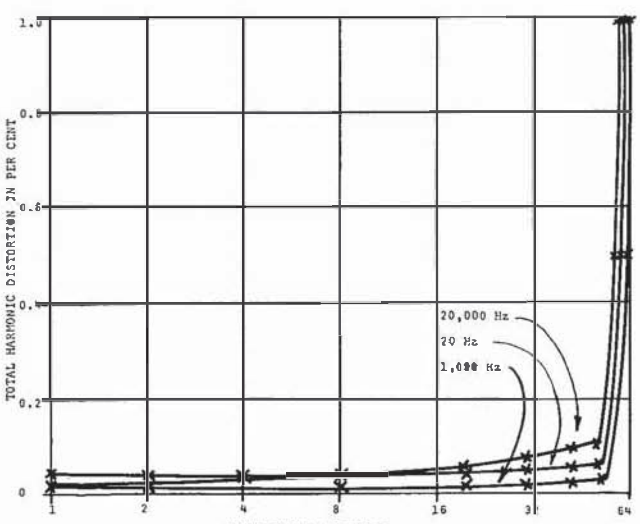

Fig. 9. Total harmonic distortion of the complete power amplifier with feedback, 8 ohm load.

Figures 8, 9 and 10 show measured harmonic distortion *vs* power output at three different load impedances and three different frequencies, with the negative feedback loop connected. These data are accurate to about ± 0.02% and the distortion measurements are of the order of 0.05%; thus, the measurement accuracy is ± 40%.

Figure 11 summarizes intermodulation distortion measurements as a function of power output into three load impedances. Into a 16 ohm load, IM distortion measures less than 0.05% at about 30 watt. At lower power levels the distortion gradually falls to the residual level of the measuring instruments, or about 0.01%. Into an 8 ohm rated load impedance, IM distortion is less than 0.1% at 50 w, and is probably nearer to 0.05%. Into a 4 ohm load, the IM distortion is less than 0.1% at 84 w.

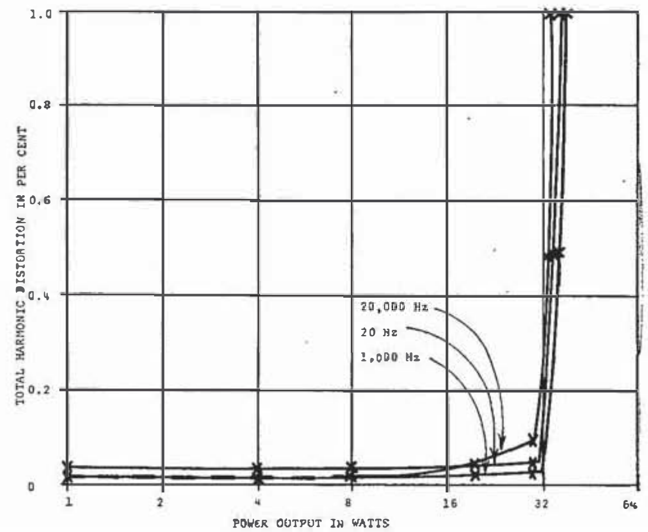

Fig. 10. Total harmonic distortion of the complete power amplifier with feedback, 16 ohm load.

Figure 12 shows the frequency response of the complete amplifier with negative feedback, at three different output power levels. Note that open-circuit response exactly matches response at 1 w output, showing that the open-circuit stability of the circuit is excellent.

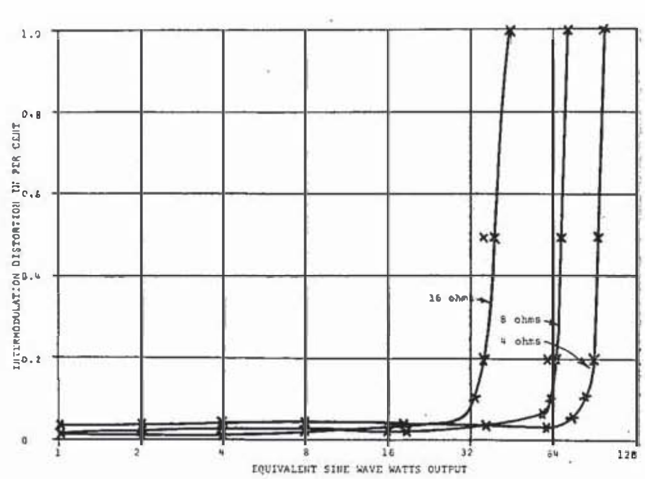

Fig. 11. Intermodulation distortion of the complete power amplifier with feedback, 60 and 7,000 Hz 4:1.

CONCLUSION

In all the commercial units incorporating the amplifier circuit described in this paper, the basic power amplifier circuit delivers 80 w (40 w per stereo channel, both channels operating simultaneously), with AC line voltage as low as 110 v, from 20 Hz to 20,000 Hz and with less than 0.15% distortion at any frequency in this range. Distortion typically is less than 0.1%. The noise level at the output terminals is less than 600 μv, typically even less than 400 μv.

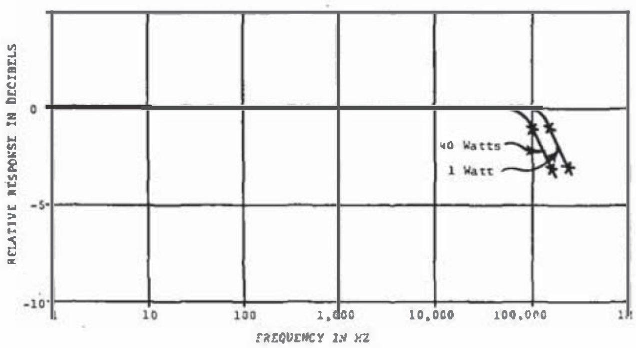

Fig. 12. Frequency response of the complete amplifier with feedback, 8 ohm load and 0 ohm source.

The two units shown in Fig. 13 are commercial models that incorporate the amplifier circuit described in this paper. The JBL Model SA600 combines the power amplifier with a preamplifier/control unit, both combined into a single chassis. JBL Model SE400S is intended for use with separate component preamplifiers. The SE400S, however, is somewhat more sophisticated than the amplifier circuit shown here; it uses plug-in equalizer boards to provide specific equalization for particular loudspeaker systems. Moreover, the equalizer board also controls a secondary negative *current* feedback loop to vary the internal impedance of the amplifier so that critical damping can be achieved for different loudspeaker systems.

It should perhaps be emphasized that the circuit is really a DC operational amplifier. It would be relatively simple, if one wished, to make a laboratory direct-current power amplifier from the design. It would be necessary to use a heat sink of greater capacity and a chopper-stabilized side amplifier. With these modifications, the circuit would become a laboratory power amplifier with a bandwidth from DC to over 20,000 Hz and a drift stability of approximately 1 μv referred to the input.

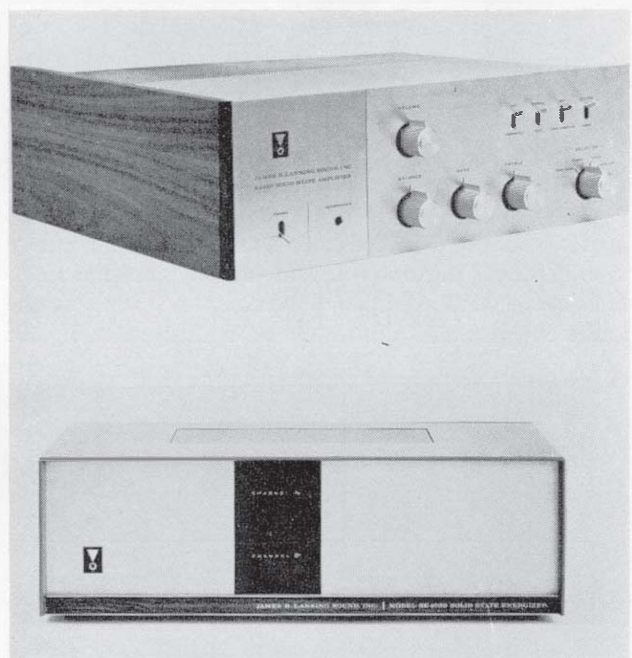

Fig. 13. (a) Model SA600 combines power amplifier with preamplifier/control unit in single chassis. (b) Model SE400S intended for use with separate component preamplifiers.

THE AUTHOR

Bart N. Locanthi was born in White Plains, New York in 1919. His education at the California Institute of Technology was interrupted by World War II, after which he returned and received a B.S. degree in physics in 1947. From 1947 to 1953 Mr. Locanthi was a part of the design group for the electric circuit analog computer at California Institute of Technology, and from 1953 to 1960 he served as chief engineer and part owner of Computer Engineering Associates, an independent firm specializing in computer components and engineering services.

Prior to 1960, Mr. Locanthi also served as consulting engineer to James B. Lansing Sound, Inc., Los Angeles. In 1960 he joined the company as vice president in charge of engineering, the position he holds at the present time.