A 14-Watt Transistor CW Amplifier with a 50-mc Bandwidth

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A transistor amplifier capable of delivering 14 watts of CW power into a 15-ohm load over a band of frequencies from 46 to 90 mc was designed for use with an FM optical modulator. This paper describes the performance and details the design and construction of the amplifier.

I. INTRODUCTION

An experimental FM optical communication system under active study required an amplifier capable of delivering a one-ampere rms signal to an optical phase modulator over a 60-mc band centered at 70 mc. The optical phase modulator[1] consists of a one-meter long 15-ohm strip line partially filled with KDP (potassium dihydrogen phosphate). The amplifier must amplify the FM input signal with a minimum harmonic distortion. Since the signal is FM modulated, the amplitude linearity of the amplifier is unimportant.

Rather than embark on a new design using stagger tuned amplifier sections, it was decided to modify a high-power transistor pulse amplifier[2] to operate as a CW amplifier. The general description of this modified amplifier appears in Section II of this paper. Amplifier performance and the modifications made to it are then described in Section III. Its design is presented in Section IV and a discussion of results is contained in Section V.

II. GENERAL DESCRIPTION

The CW amplifier consists of a power amplifier driven by a preamplifier. The power amplifier uses two UHF silicon power transistors, RCA type 2N2876, in a common-base configuration coupled at the input and output with broadband transformer hybrids. The preamplifier is a three-stage amplifier using broadband transformer coupling. It uses a UHF silicon transistor, RCA type TA2307 (2N3375), in the common-base configuration.

The complete amplifier delivers a 0.98-ampere rms signal to a 15-ohm load impedance over a band ranging from 44 mc to 90 mc and centered on 67 mc. The amplifier has a gain of 21 db and requires a 60-ma signal in the 50-ohm input line for a full output of 14.5 watts. The circuit diagram of the power amplifier and the preamplifier is shown in Figs. 1(a) and (b). The transformer hybrids and the coupling transformers are of the type described by Ruthroff.[3]

The total dc power required is 33 watts: a V_{CB} of 28 volts and a total I_C of 0.8 ampere for the power amplifier, and a V_{CB} of 32 volts and a total I_C of 0.32 ampere for the preamplifier. At the full output of 14.5 watts, the efficiency of the complete amplifier is 44 per cent.

The power amplifier is 3 inches wide, 1 inch deep and $1\frac{3}{4}$ inches high. The preamplifier is 1 by 1 by 4 inches. The total volume of the complete amplifier excluding the heat sinks is $9\frac{1}{4}$ cubic inches. The amplifier is shown in Figs. 2(a), (b), and (c).

III. PERFORMANCE*

The maximum power dissipation of the power amplifier transistors limits the output power that can be obtained from CW operation of the pulse amplifier. The 14.5-watt output in the 15-ohm load impedance was obtained by experimentally adjusting the drive and the transistor bias conditions to obtain a class AB mode of operation. This mode of operation as used in this amplifier over the frequency band of interest gives the maximum power output with minimum distortion.

The frequency response of the complete amplifier consisting of the preamplifier and power amplifier is shown in Fig. 3. The maximum power output was obtained at 50 mc with upper and lower 3-db frequencies of 90 mc and 44 mc, respectively. Examples of the output wave shape for a sine wave input are shown in Fig. 4. The first scope picture, Fig. 4(a), shows some distortion present at 46 mc. The remaining two photographs, Figs. 4(b) and (c), show no distortion present at 70 mc and 90 mc, respectively. The distortion evident at 46 mc becomes smaller and disappears at 55 mc. A fall off in response from 60 mc to 100 mc of 6 db per octave was required by the characteristics of the FM modulator.

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* These measurements were taken with a Hewlett Packard 185A sampling scope with the coaxial probe across a 50-ohm load. The 15-ohm output terminal of the power amplifier was connected to the 50-ohm line through a 0.01-μf coupling capacitor and a 1:4 broadband transformer. The location of this transformer and the 50-ohm type N output connector are shown in Fig. 2(a).

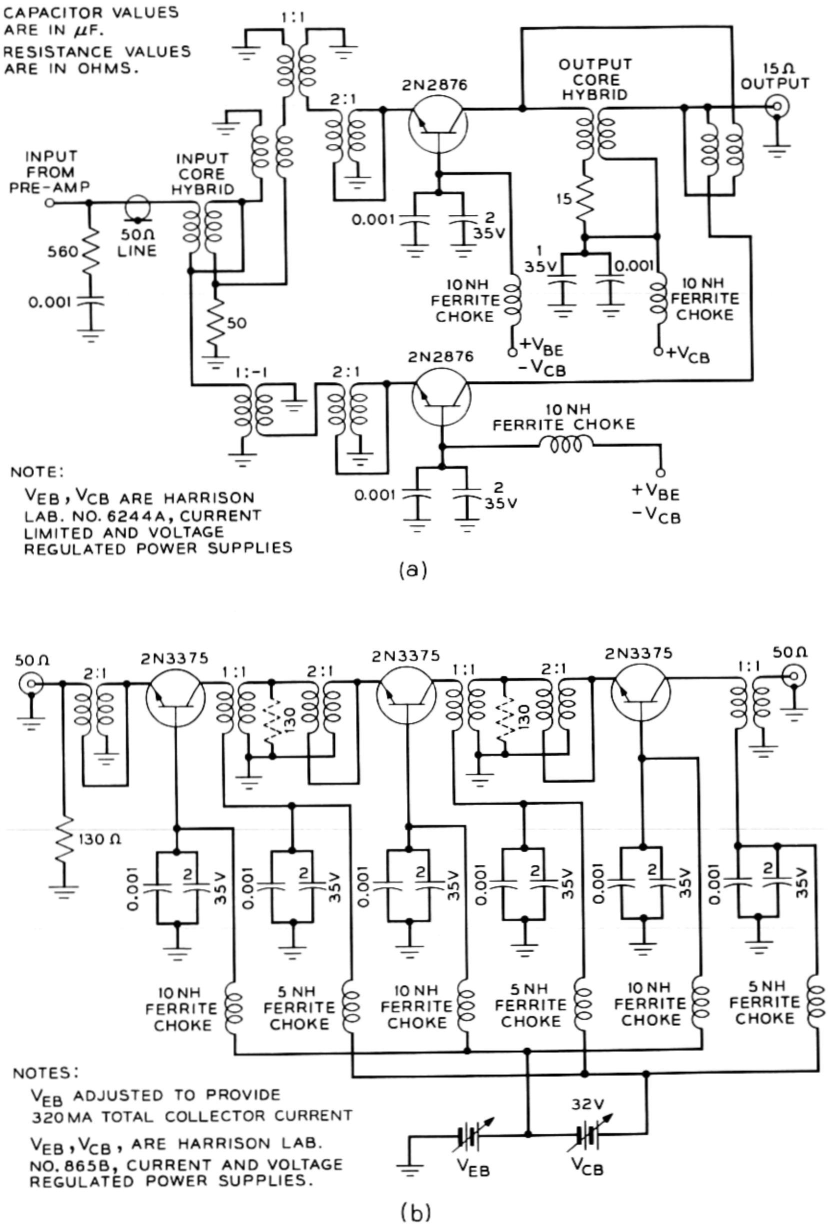

Fig. 1 — (a) Power amplifier schematic diagram; (b) preamplifier schematic diagram.

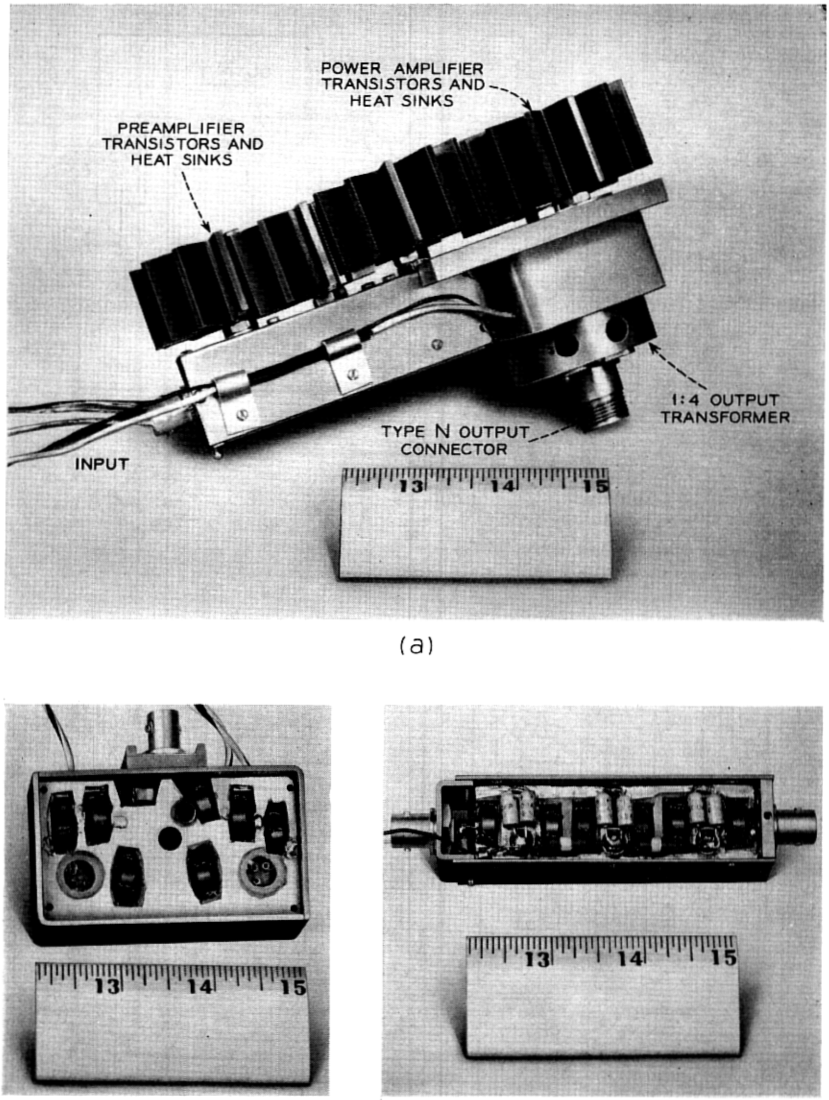

Fig. 2 — (a) Side view of complete amplifier; (b) top view of interior of power amplifier; (c) bottom view of interior of preamplifier.

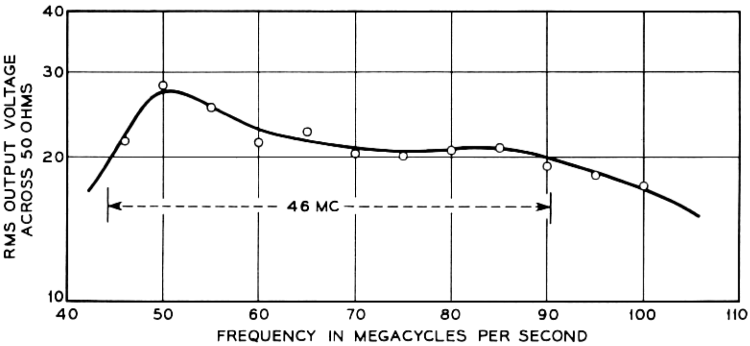

Fig. 3 — Frequency response of CW power amplifier for a 1.6-volt rms drive.

The distortion present in the output of the power amplifier results from the use of the class AB operation. In this bias condition, the transistor is operated at a collector current between that necessary for class A operation and that necessary for cutoff. Since the two transistors in the power amplifier are operated in a push-push configuration rather than a push-pull one, the second harmonic distortion is not cancelled in the output. However, by operating only over a band of frequencies from the upper 3-db frequency, $\omega_{\mu \, 3 \, db}$ to one half this frequency, the second harmonic distortion is filtered out by the amplifier itself.

In addition to harmonic distortion, class AB operation causes rectification of the input signal. This can produce additional direct current in the collector and emitter of the transistor with an increase in the dc power dissipation in the transistor.

Under class AB bias condition, an increase in the emitter drive

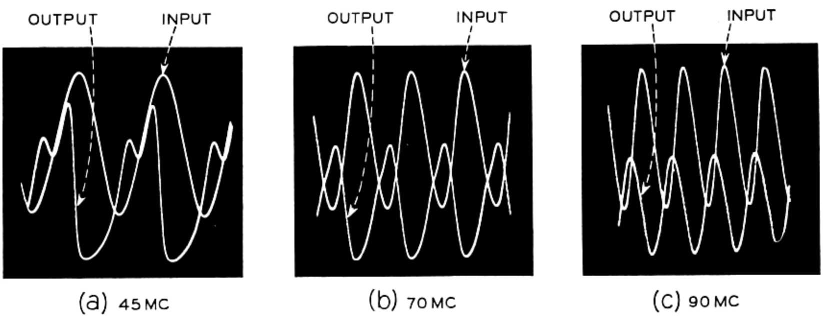

Fig. 4 — CW power amplifier output wave shapes.

causes the emitter-base junction of the transistor to become reversed biased over a portion of the RF cycle. The effect of the reversed biased emitter-base junction is to cause rectification of the emitter signal and the increase in dc emitter current. In order to prevent an increase in the collector current with drive, both the emitter and collector bias supplies were current-limited in the absence of signal to a predetermined level.

A further increase in the emitter drive causes the transistor to be driven into the saturation region where the collector current depends only on the collector supply voltage and the load. The nonlinearity associated with the transition to this region causes an increase in the dc collector current. The use of the current-limited bias supplies prevents this increase.

The bias and drive conditions for class AB operation of the power amplifier were determined experimentally. The total collector current to the two transistors was limited to 0.9 ampere with a collector voltage of 28 volts. The emitter bias was adjusted to provide a limited total current of 0.9 ampere in the absence of signal. The drive was increased until a maximum output power with minimum distortion was obtained. Under these conditions the total collector current was 0.8 ampere.

These bias conditions correspond to a dc power dissipation of 11.2 watts per transistor. Approximately 5.5 watts of RF drive were required for full output. To obtain the 14.5-watts output, each transistor must supply 4.5 watts of RF power. The total power dissipation, the sum of the RF and dc power, is 15.7 watts per transistor. The maximum allowable dissipation of the 2N2876 transistor at a 25°C case temperature is 17.5 watts. A derating factor of 1 watt per 10°C rise in case temperature is required. The case temperature rise of the transistors in the power amplifier was held at 10°C or less through the use of heat sinks and copious quantities of cooling air.

The preamplifier is operated in class AB under current-limited bias conditions also. The three 2N3375 transistors are operated from a common-collector bias supply and a common-emitter bias supply. The total collector current was limited to 0.32 ampere at a collector voltage of 32 volts. The emitter current was limited to 0.34 ampere under no-signal conditions. An input signal of 60 ma to the preamplifier in the 50-ohm input line is required to drive the power amplifier to the full output of 14.5 watts.

The need for class AB operation rather than class A operation is evident when one examines the transistor characteristic curves and the region of second breakdown. For class A linear operation of the power amplifier, an rms collector current of 0.5 ampere is required to obtain the 15-watt output. Thus the peak collector current is 0.71 ampere. With the nominal α of 0.9, we need a peak emitter current of 0.79 ampere. The peak collector voltage across the 30-ohm load seen by each transistor is 22 volts. The class A bias points must be at a collector current and voltage somewhat greater than these values to prevent distortion due to the nonlinear transistor characteristics at the peak value of current. For a collector voltage of 26 volts and a bias current of 0.75 ampere, the transistor is in a region of second breakdown for class A operation.

The 60-ma input signal required to drive the power amplifier to its full output could not be supplied by the IF amplifier used in the FM system. A second preamplifier was designed to amplify the +5 dbm output of the IF amplifier. This amplifier was of the same basic construction as the preamplifier used to drive the power amplifier. The original preamplifier had a rising output with frequency to compensate for the fall off of the power amplifier. In order to flatten the frequency response of the second preamplifier, it was necessary to add a 130-ohm, $\frac{1}{8}$-watt resistor across the output of each collector transformer. These resistors are shown dotted in the circuit diagram of the preamplifier in Fig. 1. The measured frequency response of this second amplifier is shown in Fig. 5.

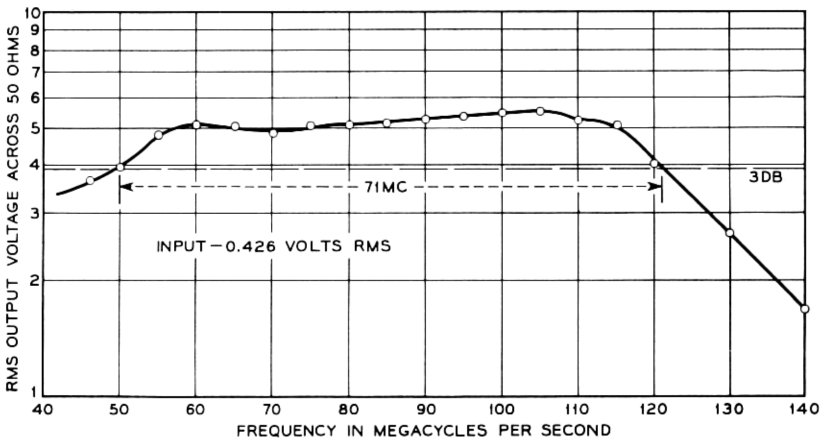

Fig. 5 — Second preamplifier response.

IV. AMPLIFIER DESIGN AND CONSTRUCTION

The operation of the power amplifier can be seen by reference to Fig. 1(a). Consider a unit current signal at a 50-ohm impedance level incident on the input transformer hybrid. Unit current signals appear at the two conjugate arms at a 25-ohm impedance level 180° out of phase. A 1:1 reversing transformer in one arm reverses the phase of one signal. A 1:1 transformer in the opposite arm preserves the phase of the signal but introduces a delay equal to that of the reversing transformer. These in-phase signals are applied to the emitter of the respective transistors through 4:1 impedance transformers. These two unit current signals applied to the emitters are at a $6\frac{1}{4}$-ohm impedance level. This level is close to the 6-ohm input impedance of the transistor in the common-base configuration. The transistor collector current using nominal short current gain, α, of 0.9 is approximately 1.8 units. The output signals of the two transistors at a 30-ohm impedance level are combined in the output hybrid to produce a 3.6-unit amplitude current signal in the 15-ohm output impedance. The power amplifier has a current gain of 3.6. Due to the class AB operation, the actual current gain will be somewhat less.

The operation of the preamplifier can be seen from the circuit diagram of Fig. 1(b). Consider a unit current signal incident at the input. The first 4:1 transformer produces a 2-unit amplitude signal at the emitter of the first transistor. Under large signal conditions the input impedance of these transistors, 2N3375, is approximately 8 ohms. Using a nominal α of 0.9, the collector current will be 1.8 units. The output of the transistor is coupled to the 4:1 transformer at the input of the next transistor through a 1:1 isolation transformer. The use of this transformer provides a path for the collector bias. The operation of the two following stages is identical with the first stage. The overall current gain is 5.83. Because of the class AB operation, the actual current gain will be less.

The current gain of a complete amplifier between the 32-ohm input impedance of the preamplifier and the 15-ohm output of the power amplifier is 23 db. Since the measured gain was 21 db, approximately 2 db of gain is lost in using the class AB bias conditions.

The basic amplifier construction uses a quasi-stripline to interconnect the core transformers and transistors. The input and output circuits are placed on opposite sides of a center board in nonoverlapping areas. Ground planes boards are placed on top and bottom of the common board. This results in a 3-layer sandwich construction. The center board is $\frac{1}{8}$-inch thick glass-loaded Teflon with 2-oz copper on each side. The ground plane boards are $\frac{1}{16}$-inch thick glass-loaded Teflon with 2-oz copper on each side. Transistor sockets were made by placing spring contacts for each pin on the transistor case into holes drilled in the center board. These contacts were made using the center conductor of a BNC female coaxial connector. After being placed into the center board, these contacts were soldered to the copper. Matching rectangular holes were cut in each board to accommodate the core transformers. The copper on the board surfaces was cut away so as to leave stripline connections between the cores and transistors. The boards were separated by placing $\frac{3}{16}$-inch thick brass spacer around the periphery of the boards. Where this spacing was not adequate for the proper stripline impedance, brass pieces were attached to the center board to decrease the spacing in a local region. The terminations for the input and output hybrids — 50 ohms and 15 ohms, respectively — were 1 watt, 1 per cent metalized film microwave rod resistors made by Film Ohm Corporation. The base by-pass capacitors consisted of a 0.001-μf feed-through capacitor mounted in the ground plane with the center conductor connected to the base terminal of the center board. Two 2-μf miniature tantalum capacitors were used in parallel with the feed-through capacitor. The collector dc connection was bypassed with a 0.01-μf postage stamp type capacitor in parallel with a 2-μf miniature tantalum capacitor. Collector bias was applied between collector-base terminals. Emitter bias was applied between base terminals and ground.

The layout of the three circuit board for the power amplifier is shown in Fig. 6. Both sides of each board are shown. The layout of the 3-transistor circuit board of the preamplifier is shown in Fig. 7. The position of the parts and the sections of stripline are evident upon examination of these figures.

The outside dimensions of the circuit boards were dictated by the space available inside the KDP modulator structure and by a need to keep all leads as short as possible. To keep the connection between the power amplifier and the KDP stripline to a minimum, the power amplifier had to be placed in a space 1-inch deep, 3-inches wide and $1\frac{5}{8}$-inches high. A mounting box of these outside dimensions was made of $\frac{1}{16}$-inch brass, and the circuit board was sized so as to fit inside this box. The transistor heat sinks, 2-inch diameter, 1-inch high 12-fin aluminum cylinders, were extended out through the end plate of the KDP mounting box. The heat sinks were mounted on the transistor package stud and kept isolated from ground. Since the collectors of the 2N2876 and TA2307 are isolated from the case (collector-to-case capacitance 6 pf), the mounting of the heat sinks in this manner reduced the col-

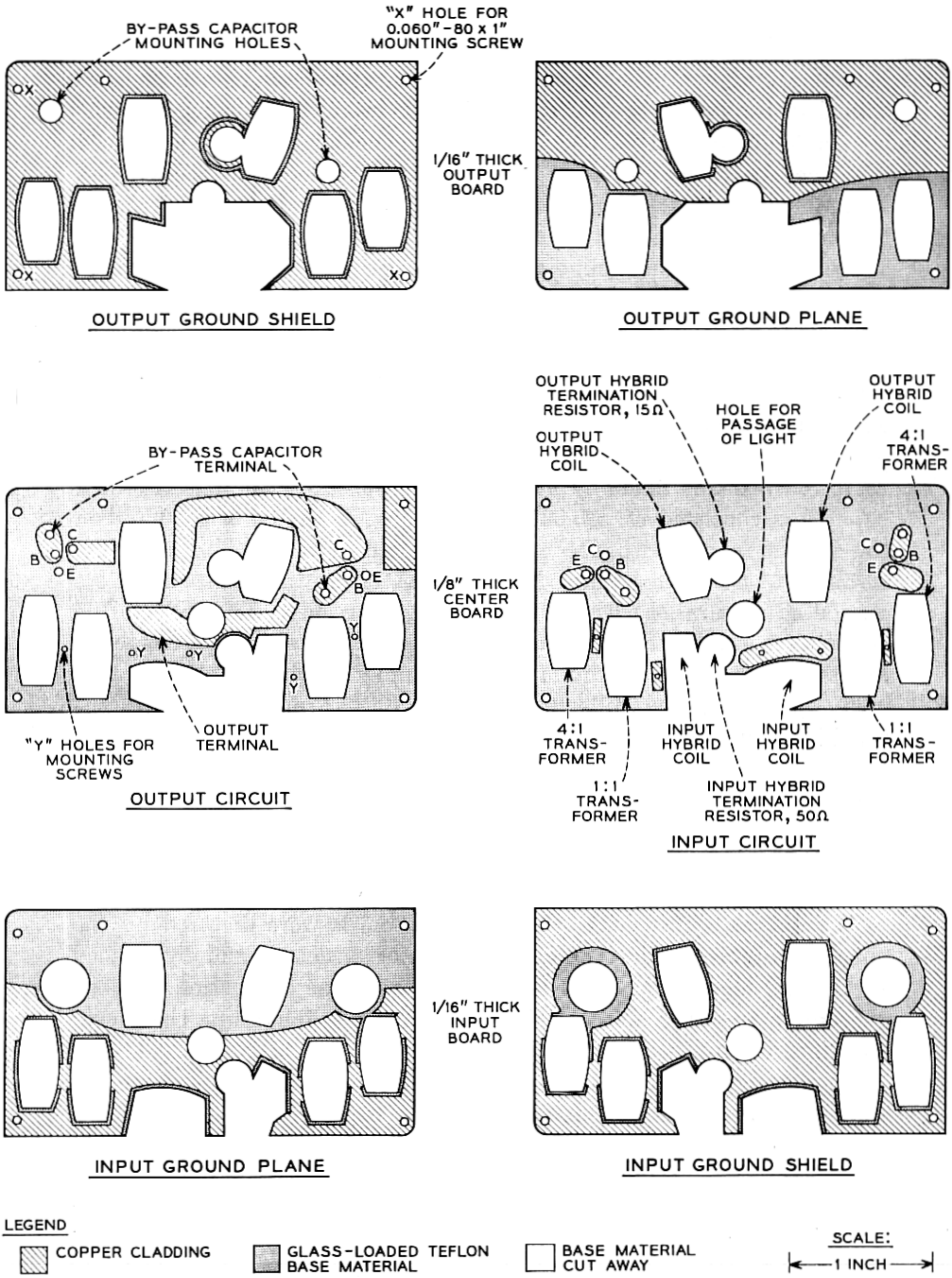

Fig. 6 — Power amplifier circuit boards.

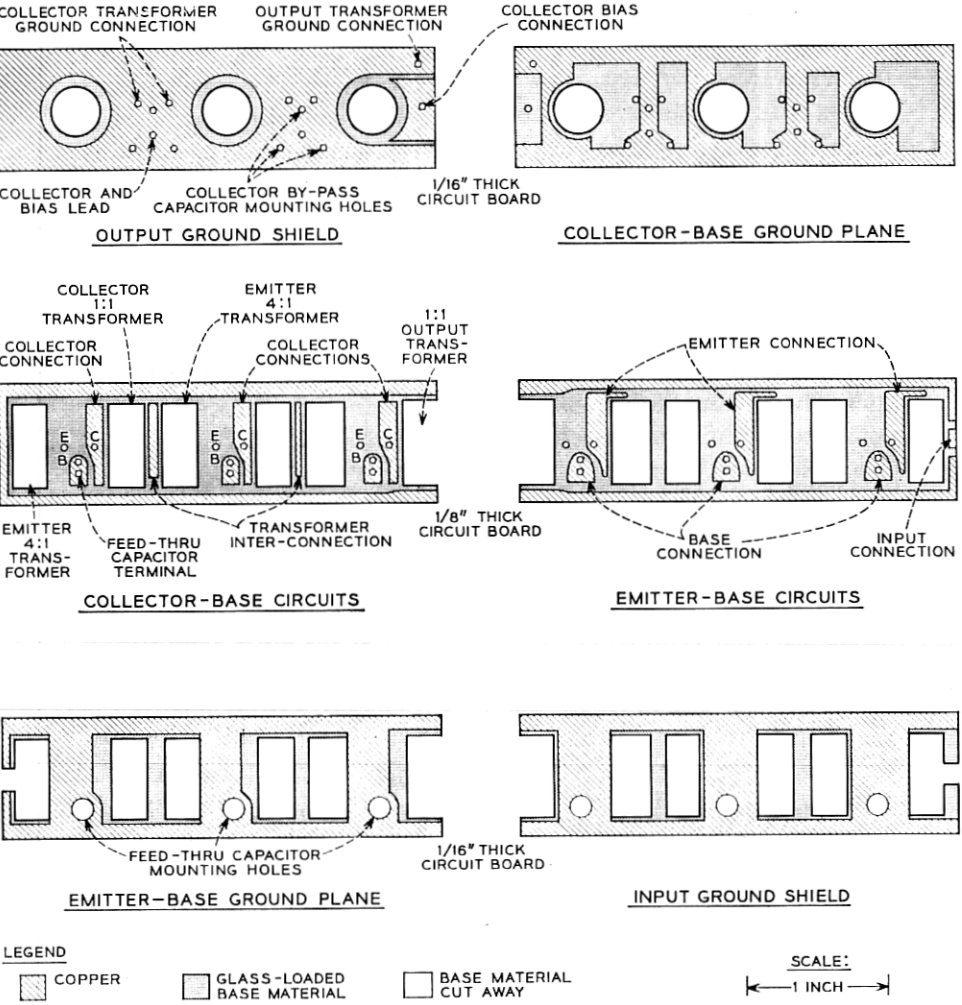

Fig. 7 — Preamplifier circuit boards.

lector circuit capacitance to a value close to the transistor collector capacitance, 20 pf for the 2N2876 and 10 pf for the TA2307.

The cores in the output hybrid of the power amplifier were bifilar wound with 6 turns of number 22 Formex wire. The transformer cores and the input hybrid cores were bifilar wound with 6 turns of number 24 Formex wires. All the transformer cores in the preamplifier except the output transformer were bifilar wound with 6 turns of number 24

Formex wire. The output transformer core was bifilar wound with 5 turns of number 24 Formex wire.

The size of the preamplifier was also dictated by the dimension of the KDP modulator structure. A narrow 1-inch by 1-inch passage existed between the top of the power amplifier and the top wall of the modulator structure. The preamplifier was mounted in a $\frac{3}{64}$-inch thick brass box 1 by 1 by 4 inches mounted on top of the power amplifier and extended through the top of the modulator structure. Connection of the preamplifier with the coaxial output of the modulation source was made through a BNC connector. The circuit boards of the preamplifiers were cut to dimensions to fit this box. The heat sinks for the preamplifier were of the same type as those of the power amplifier. Certain fins of each heat sink were cut away so that the heat sinks of successive preamplifier transistors could interleave. The details of the complete amplifier can be seen in Figs. 2(a), (b) and (c).

V. DISCUSSION

The broadband transformer-coupled transistor pulse amplifier has been shown capable of high-power CW operation. CW output power up to 14 watts into a 15-ohm load was obtained over a 46-mc band extending from 44 to 90 mc. CW operation of the pulse amplifier was obtained by using class AB bias with current-limited power supplies. The distortion generated by this bias condition was eliminated from the output by using the amplifier as its own filter. This scheme of filtering is useful for operation over a band of frequencies extending from the upper 3 db frequency of the amplifier to one half this frequency. A second amplifier with selected transistors, matched in amplitude and phase of the α response, delivered 9 watts ± 1.5 db with a 3-db bandwidth extending from 70 mc to 140 mc. As a comparison, a similar amplifier operated with class A bias can deliver 5 watts to the 15-ohm load with some distortion over a band extending from 19 mc to 86 mc. Several of these amplifiers have been in daily use for several months. There has been no degradation in their performance during this period.

With the advent of this family of high-power UHF and VHF silicon power transistors using a novel overlay construction, it is possible to design broadband high-power CW and pulse amplifiers that operate into low impedance loads. With a staggered tuned amplifier design it should be possible to obtain output powers of 10 or more watts over wide bands centered in the 100- to 300-mc region. Future effort could well be directed in this direction.

The success of the amplifier described in this paper is due to large part to the ability of J. W. Batton. He was able to accurately construct and align the stripline segments that make up the major interconnection network of the amplifier.

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