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RESEARCH AND DEVELOPMENT

OF

AN OPTIMIZED LABORATORY SPEECH-COMPRESSION SYSTEM FOR SPACECRAFT APPLICATION

TASK 7

MICROMINIATURIZATION STUDY

Contract No. NAS 9-4523

25 May 1966

Manned Spacecraft Center
National Aeronautics and Space Administration
Houston, Texas

PHILCO CORPORATION
A Subsidiary of Ford Motor Company
Communications and Electronics Division
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SECTION 1

INTRODUCTION

The purpose of this report is to determine definitive information towards developing a microminiature speech-compression equipment from the existing discrete component breadboard system that was developed on the program.

The body of the report is contained in Section 2, FACTUAL DATA. This Section is divided into two parts to discuss:

a. The Microcircuit Technology in relation to the major approaches available, reliability, size, weight, maintainability, power dissipation, and cost.

b. The suggested design approach to effect the most feasible approach to microminiaturization of the breadboard unit.

SECTION 2

FACTUAL DATA

2.1 DISCUSSION OF MICROCIRCUIT TECHNOLOGY

2.1.1 Microelectronic Components

In the portions of any system where the techniques are applicable, microminiaturization offers distinct advantages over conventional methods. These areas of the system are reliability, maintainability, cost, size and weight, and power dissipation. A discussion of the advantages to be realized, particularly in regard to reliability and size and weight are presented in the following paragraphs.

2.1.1.1 Reliability

The projected increase in reliability obtainable with microelectronic circuitry is based, first of all, upon the use of the silicon planar process with its surface passivation, which has been proven to yield high-reliability devices. This process is used to fabricate the transistors and diodes of thin-film or thick-film circuits, and to fabricate the entire circuit in the case of solid-state microelectronic circuits.

Second, microcircuits have more reliable intraconnections. In the case of solid-state circuits, for example, the intraconnections on the silicon chip are made with aluminum film interconnect pattern. The aluminum film is alloyed to form the junctions with various semiconductor elements. Thermocompression bonds are used to connect the silicon chip to the package leads. The same is the case for thin-film and thick-film circuits, except that the intraconnection pattern is made of a silver or gold metallic film fired on the ceramic subtrate.

Third, a much higher degree of process control is possible when fabricating microcircuits than when assembling conventional component circuits. Also, the completed circuit is enclosed in a small, hermetically sealed package, which tends to buffer the circuit from environmental stresses which often cause failures in conventional component circuits. The small size and mass of the entire package makes it less susceptible to failure from shock and vibration.

2.1.1.2 Size and Weight

That the size and weight of microcircuits have been reduced by an order of magnitude over conventional component modules is, of course, obvious. Solid silicon integrated circuits are available in flat packages 0.25 by 0.25 by 0.125 inch. This compares to a standard cordwood module of 1.5 by 0.50 x 0.75 inches. Thin-film circuits are available in flat packages 0.25 by 0.375 by 0.125 inch and thick-film circuits in flat packages 0.375 by 0.375 by 0.125 inch. The weight of a microcircuit module is less than 0.3 gram.

2.1.1.3 Maintainability

The maintainability of an equipment using microcircuits is enhanced because replacement is essentially done on a whole-circuit basis, thereby reducing the downtime. Another advantage which aids in maintainability is that the use of microcircuits generally results in a standardization of parts, and hence alleviates the spare parts problem.

2.1.1.4 Cost

Microcircuits have been shown to have a cost advantage over conventional component circuits for many applications. There are three main reasons for this. First, all microcircuit techniques are essentially a batch process; that is, whole circuits, or at least parts of circuits, and intraconnection patterns are made at one time. Second, assembly and source testing are performed by a single vendor, which reduces the amount of component handling. Third, the microcircuits user has a much simpler parts management problem and can save considerable time and money.

2.1.1.5 Power Dissipation

In general, the power dissipation of a microcircuit is much lower than a conventionally packaged unit. One reason for this is that silicon planar transistors, which must be used, have high gains at low current levels. Another reason is that low-power circuit designs may be accomplished by taking advantage of resistor ratio tolerances and thermal tracking of the internal elements.

2.1.2 Microelectronic Technology

There are four major approaches presently available for the microminiaturization of electronic circuits; these are silicon solid-state, thin film, thick film, and MOS. A brief description including performance capability of these four approaches is presented in the following paragraphs.

2.1.2.1 Silicon Solid-State Technology (Semiconductor MeFD)

Silicon solid-state circuits are currently enjoying a period of tremendous growth, especially in the digital area. The milliwatt logic modules suggested for this program are solid-silicon circuits. In this approach the planar process is used to fabricate a complete circuit on a homogeneous single-crystal semiconductor whose dimensions are approximately 0.1 inch by 0.1 inch. The term "planar process" signifies that all p-n junctions associated with the circuit are terminated at the surface of the silicon dioxide (formed by the thermal oxidation of the silicon material) which acts as a shield against contamination, thus yielding better reliability. Another important feature of this process is that many circuits are fabricated at one time, leading to a further increase in reliability and decrease in cost.

The microcircuit elements (transistors, resistors, diodes) are formed by diffusing boron (p-type material) into selected areas of the n-type silicon chip. The process actually involves three diffusions; however, the first serves only as an electrical isolator between circuit elements.

Small whisker wires, thermocompression bonded to the silicon elements, are used to connect the silicon circuit to the external package. All other intraconnections are made by an aluminum film overlay.

Although the silicon solid-state approach is restricted at very high frequencies, it is excellent for use in audio circuits and medium speed logic.

Consider the component range of values and tolerances which can be attained using this method of fabrication. The range of resistor values is limited from 100 ohms to 50,000 ohms (practical upper limit 20,000) with from a ±5 percent to ±20 percent tolerance. The temperature sensitivity ranges from 50 to 5000 ppm/°C, with a typical value being 1000 ppm/°C. The silicon solid capacitor is usually nothing more than the capacity associated with a reverse-biased p-n diode, although a silicon dioxide capacitor may also be fabricated. The range of capacitor values is approximately 10 pf to 2000 pf with a practical upper limit of 500 pf; of course, this value varies with the applied reverse bias. The tolerance of capacitors is poor, ranging from ±10 percent to ±50 percent depending on the capacitor value; the temperature sensitivity is about 200 ppm/°C, and the breakdown voltage varies from 5 to 100 volts. Almost any normal silicon planar diode or transistor may be fabricated in integrated form.

From the above information, one may conclude that the solid-silicon approach is most amenable to the design of digital circuits. Low-frequency (audio) analog circuits are also easily fabricated provided large-value capacitors or precision resistors are not required.

The technique of deposition in conjunction with silicon presently exists. This involves the depositing of passive films on silicon to form resistors and capacitors. However, capacitor values are still limited to relatively low values (≈ 1000 pf).

2.1.2.2 Thin-Film Technology (Thin-Film MeFD)

A second approach to microminiature circuits is the thin-film technology. In this approach a thin film of metallic material is sputtered or evaporated on a smooth substrate, usually glass. The metallic films are usually either tantalum, nichrome, tin oxide, or titanium. Photolithographic techniques are then used to form the desired pattern of resistive and conductive elements, while the capacitors are formed by anodizing and replating selected areas of the conductor pattern. Since a good thin-film active device does not presently exist, silicon planar diodes and transistors are added as chip elements. The thin-film amplifier-limiter (Standard Analog Stage) developed by Philco (Lansdale) for use in Vocoders is shown in Figure 2-1.

The thin-film approach offers the advantage of greater range of values, tighter tolerances, and lower temperature sensitivities. Resistor values range from 50 ohms to 1 megohm, with a practical upper limit of 100,000 ohms. Tolerance is normally ±10 percent but may be made as low as ±0.5 percent. Temperature sensitivities range from -300 to +200 ppm/°C, with a typical value being +100 ppm/°C. Capacitor values range from 10 to 25,000 pf, with a practical upper limit of 10,000 pf. A capacitor tolerance of from ±5 percent to ±20 percent is easily obtained; the temperature sensitivity is 100 ppm/°C. Capacitors with Q's of 10 at 10 Mc and Q's of 50 at 1 Mc have been fabricated. Voltage breakdown values range from 5 to 50 volts.

2.1.2.3 Thick-Film Technology (Hybrid MeFD)

Thick-film circuits are sometimes called ceramic printed circuits. These names are derived from the fact that a noble-metal resistive film is printed or screened onto a ceramic substrate. These films are thicker (2000 to 3000 Å) than the thin film (200 to 300 Å) mentioned previously. The conductor intraconnection pattern is silver; however, the transistors and diodes are silicon planar as in the thin-film approach.

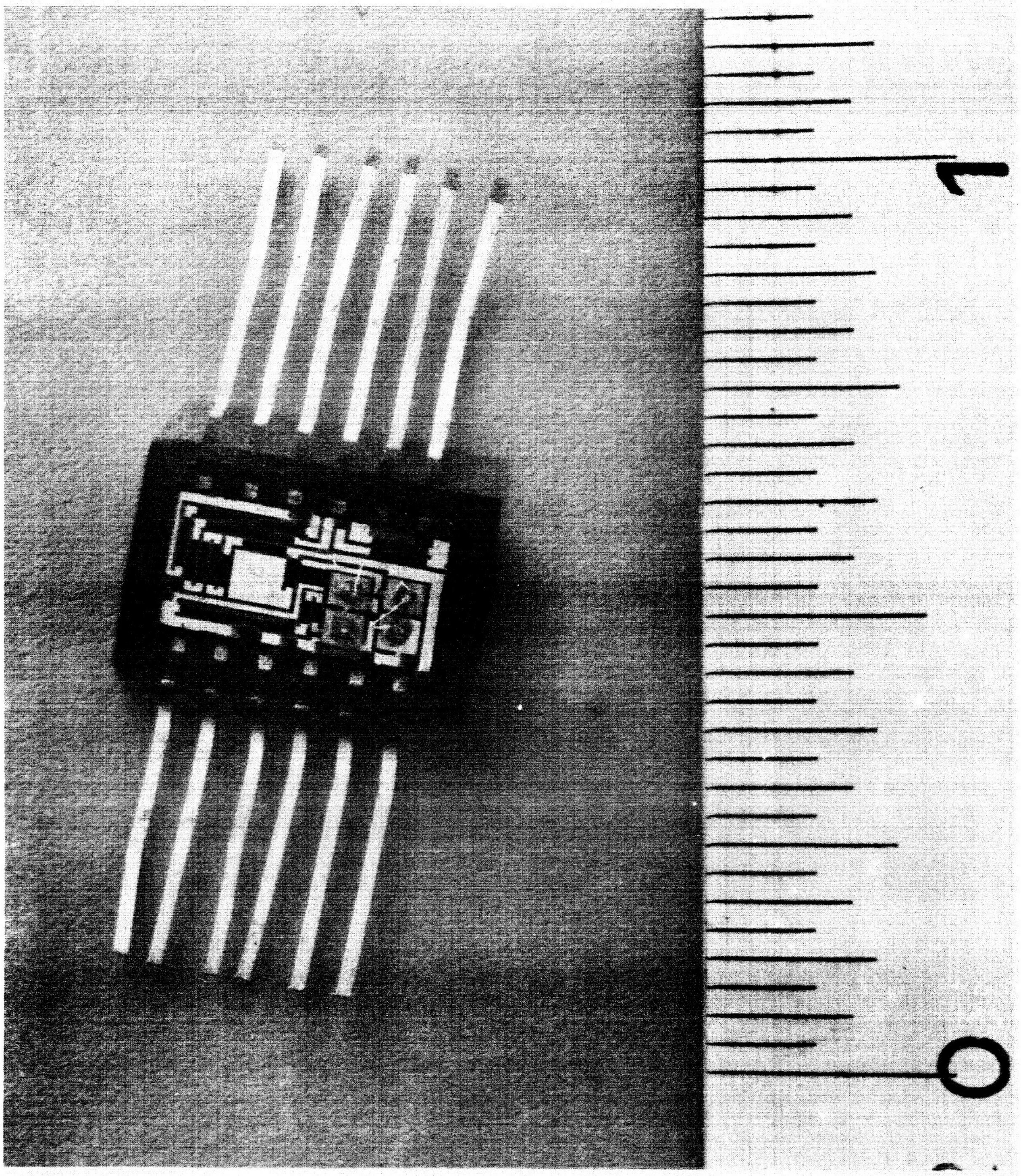

Figure 2-1. Thin-Film Amplifier Limiter

Barium titinate, ceramic or tantalum slugs are used as the capacitive elements. All connections from semiconductor elements are made by thermocompression bonding. The connections from the conductor pattern to the package are made with copper-solder preforms.

Figure 2-2 shows the production sequence of a three and four substrate thick-film circuit. First, the gold platinum conductor pattern is plated on the ceramic substrate; next, by a screening process, the resistors are formed; and finally, the unit is fired in an oven. This results in a metal-glazed or passivated resistor. The silicon transistors and diodes are then attached to the silver conductor pattern as are the capacitors. Next, all thermocompression bonds are made by using whisker gold wires. The next steps are to assemble the wafers and copper-solder preforms. The entire unit is then dipped into a hot silicone bath so that all solder joints are made at once. The last step is to weld the top cap to the header. Figure 2-3 shows a picture of three different wafers and also a completed unit. Wafer a contains two transistors; Wafer b, two resistors and a capacitor; and Wafer c contains four resistors. Notice the whisker wires and thermocompression bonds as well as the copper-solder preforms on the completed unit.

The thick-film approach offers approximately the same range and tolerance of component values as does thin film. Resistor values range from 10 ohms to 1,000,000 ohms, with a practical upper limit of 500,000. Tolerance is normally ±10 percent but ±2 percent is obtainable at a very small additional cost. The metal-glaze resistors meet MIL-R-10509D, and MIL-R-22684A. Temperature coefficients are about 300 ppm/°C. Standard capacitor values range from 20 pf to 1,000 pf and into the microfarad range for special cases. A capacitor tolerance of ±10 percent is normal. Capacitor Q's at 1 Mc are above 50 and voltage-breakdown range is from 10 to 100 volts.

Thick-film circuits for the Air Force and USAERDL Vocoders with passive elements on one side of the ceramic substrate are available and have been developed during the Philco's Microminiature Study program in TO-5 cans. If passive elements are screened on both sides of the ceramic substrate, circuits are available in 0.375- by 0.375-inch flat packs and in some cases 0.25 by 0.375 inch may be attained.

2.1.2.4 MOS Technology; General

Up until 1964 MOS-FET devices were not mass manufactured because of the problem of reducing surface impurities. In 1964 this

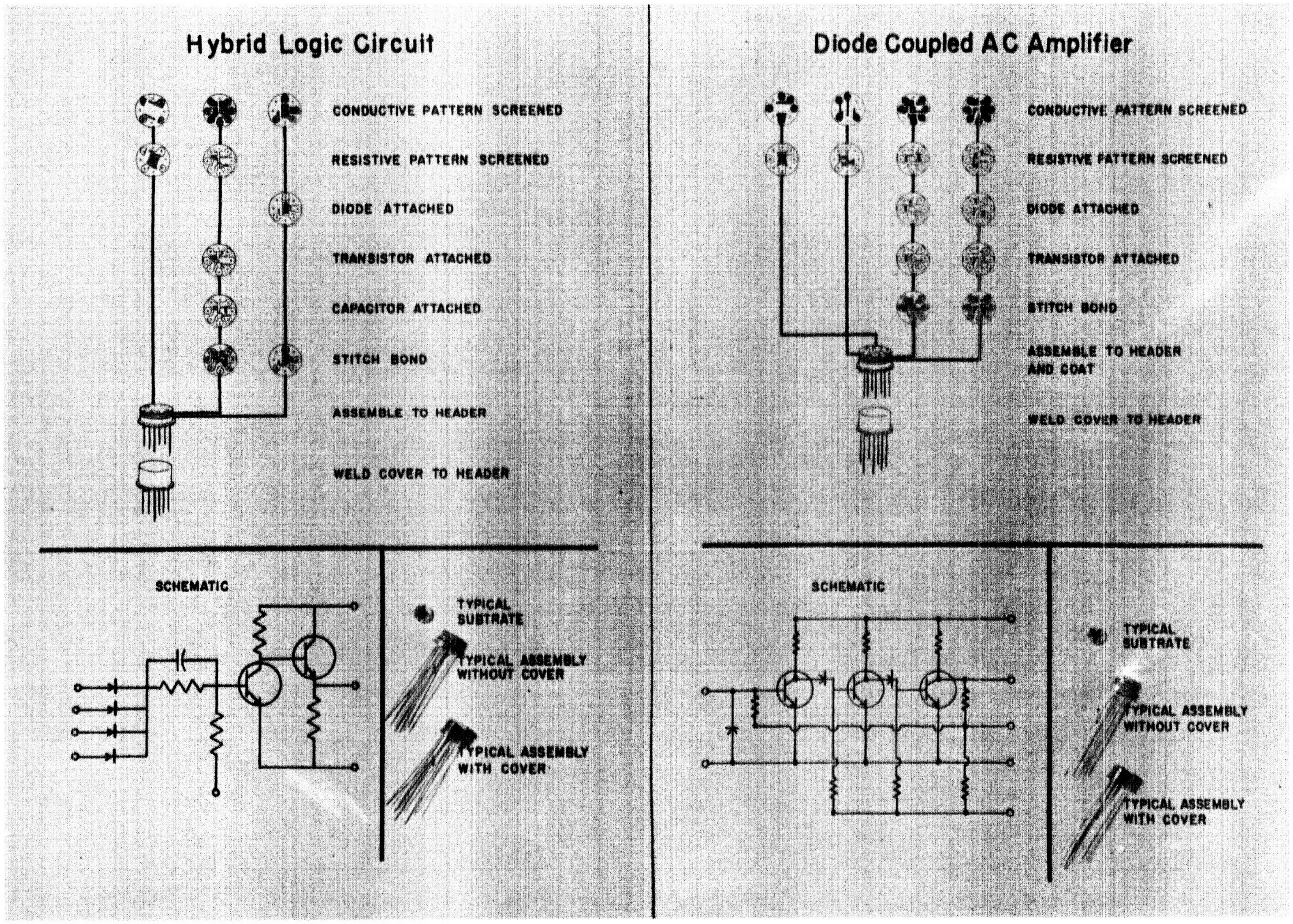

Figure 2-2. Substrate Thick-Film Circuit Fabrication

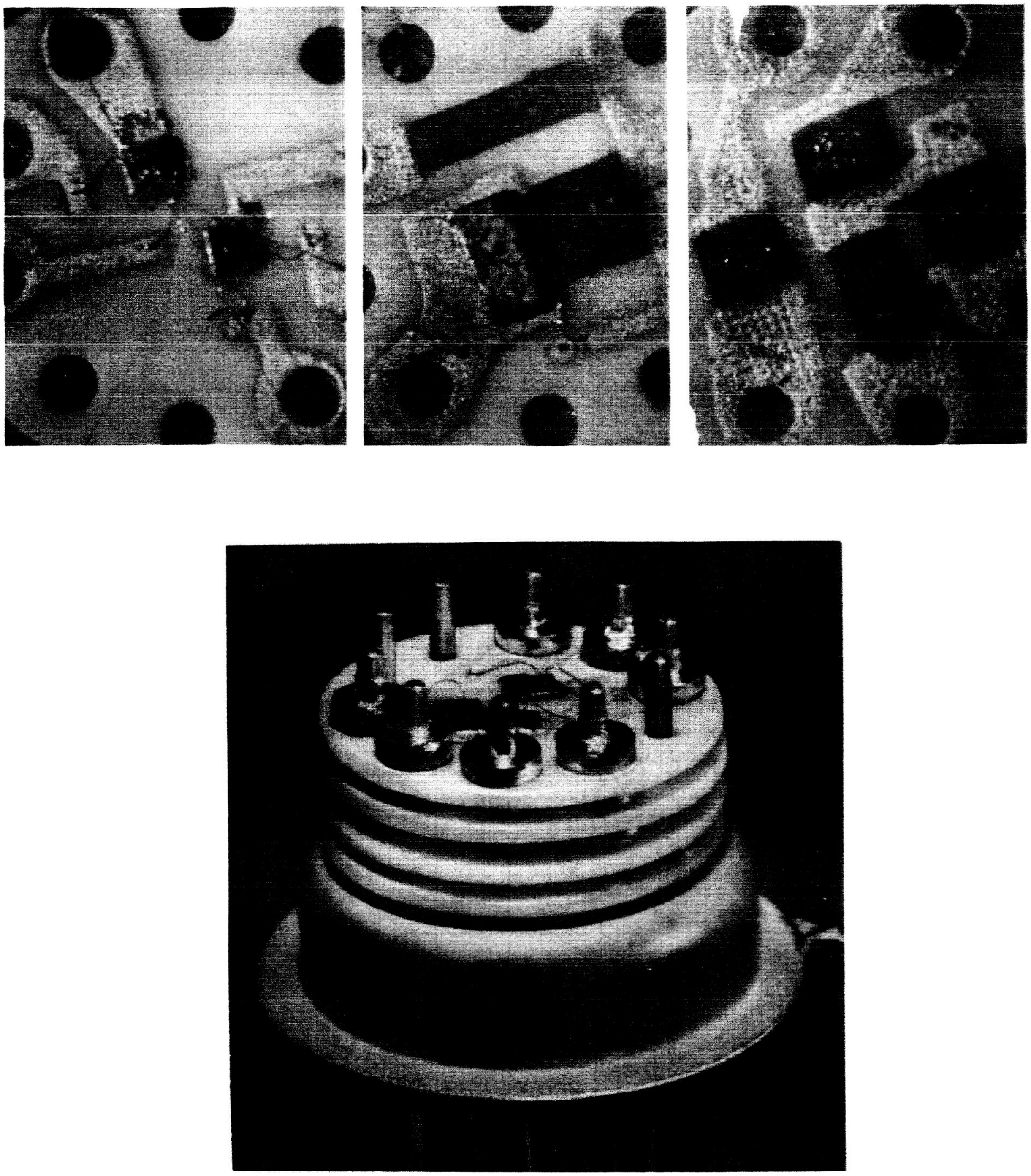

Figure 2-3. Substrate Thick-Film Unit

problem was solved and several companies have developed a carefully controlled process for the manufacture of stable MOS devices.

The MOS technology is of interest for the following reasons:

a. Extremely high input impedance (active filters)

b. Device isolation

c. Small geometry

d. Single diffusion

e. When used as resistor, it provides very high ohms/mil^2 (25 kilohms)

f. Low power

Input impedances of the basic MOS/FET are in the order of 10^{14} to 10^{18} ohms. Such a characteristic could be very useful in active-filter design.

The double-diffusion process required in the monolithic bipolar silicon technology is not necessary because isolation diffusions are eliminated. Process-wise, two masking steps, two diffusions (collector and isolation), and epitaxial growth are eliminated.

The basic MOS transistor utilizes less than two square mils of area, whereas an integrated bipolar transistor would require approximately 48 square mils.

The single-diffusion process required to manufacture an MOS device increases yield and eases the task of controlling certain component parameters.

An active MOS device can be utilized as a resistor in the "ON" mode. When used in this manner it has the following advantages over common diffused or even thin-film resistors.

a. Extremely small device having a very high ohms-per-square of approximately 25 kilohms.

b. An active device for a load resistor whose temperature coefficient matches that of the inverter.

c. A load resistor whose magnitude is a function of transconductance and therefore tracking with the transconductance of the inverter.

Since the MOS/FET has a very high input impedance the driving capabilities between MOS/FET units is extremely good. Very low power is required for driving other stages.

2.1.3 Analog Circuits

This selection of a technology to fabricate analog circuits is a more subtle decision than in the case of the digital circuits. A general-purpose amplifier-limiter has been fabricated by Philco in all three technologies, solid silicon, thin film, and thick film. As should be expected, the electrical performance of the thin-film and thick-film circuits was both good and about equal. The electrical performance of the solid silicon version was not as good as that of the film versions. Because of this, and the fact that solid-silicon circuits are quite expensive in small quantities, this approach does not look too promising. Either the thin-film or thick-film versions could be used successfully; however, there does exist at present a larger amount of documented life data for thick-film circuits than for thin-film. It is Philco's position that, inherently, both technologies are very reliable and indeed there is no reason to believe that the thin-film approach is any less reliable than the thick-film approach. Analog modules similar to the ones needed on this program have been built by Philco and are shown in Figure 2-4.

2.2 NARROW-BAND SPEECH-COMMUNICATION MICROMINIATURE CIRCUIT STUDY

2.2.1 Circuit Guidelines for the Study

For this study the following basic rules are assumed:

a. No changes will be made to the overall block diagram or to the basic system philosophy.

b. Design approach of individual blocks may be changed to facilitate the application of microcircuit techniques.

c. Integrated single-chip circuits will be used where a size saving or increased performance can be obtained.

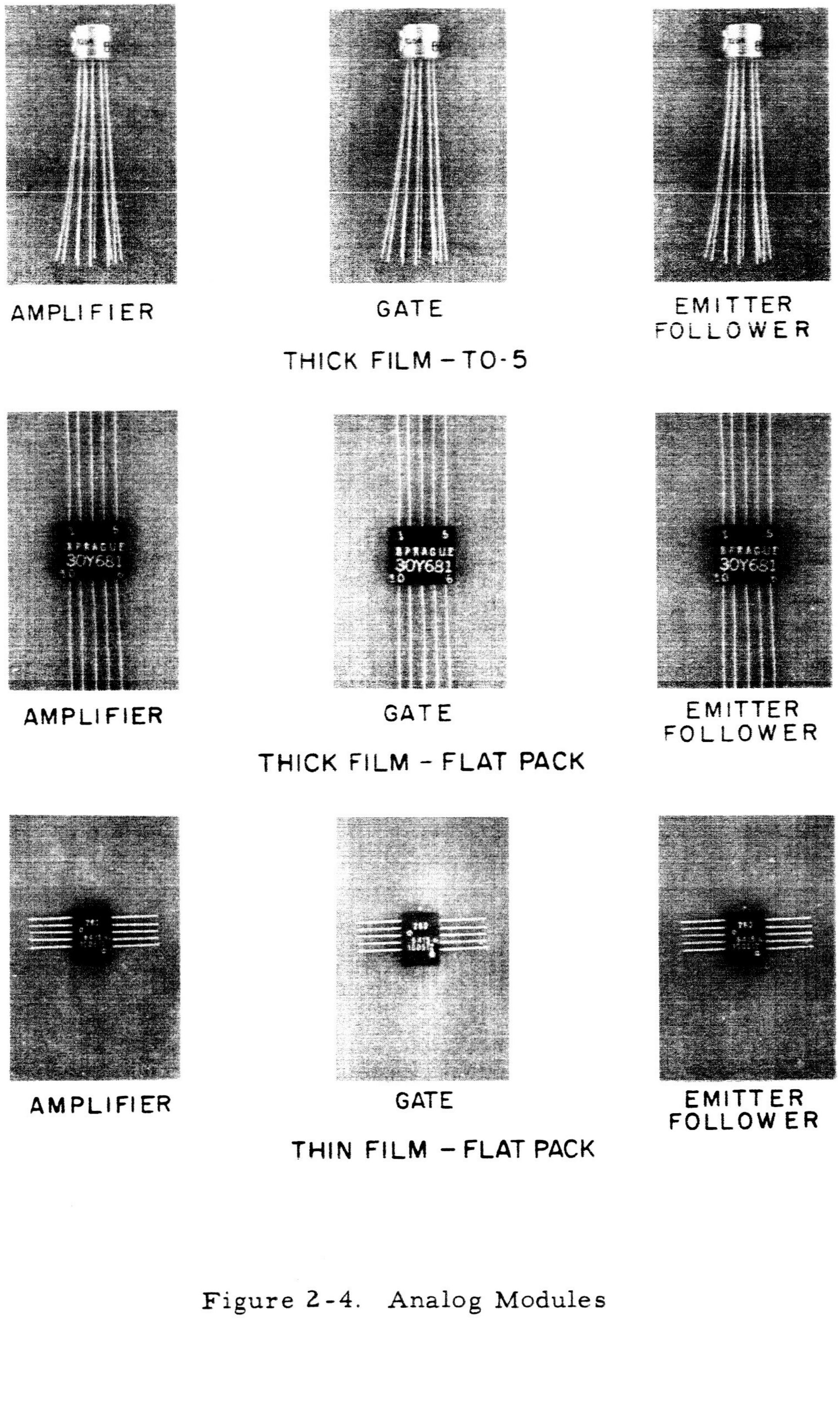

Figure 2-4. Analog Modules

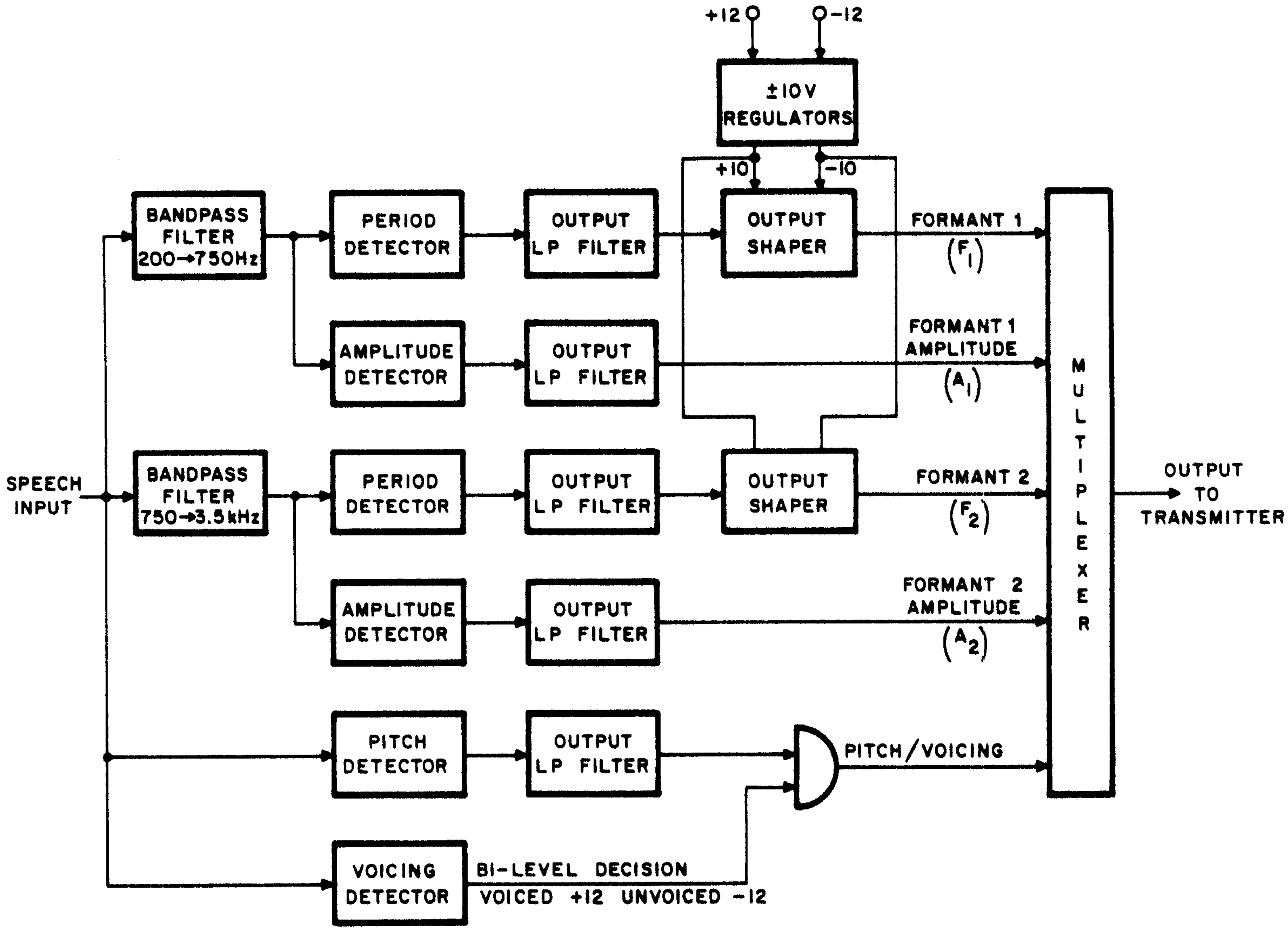

Figure 2-5. Analyzer, Block Diagram

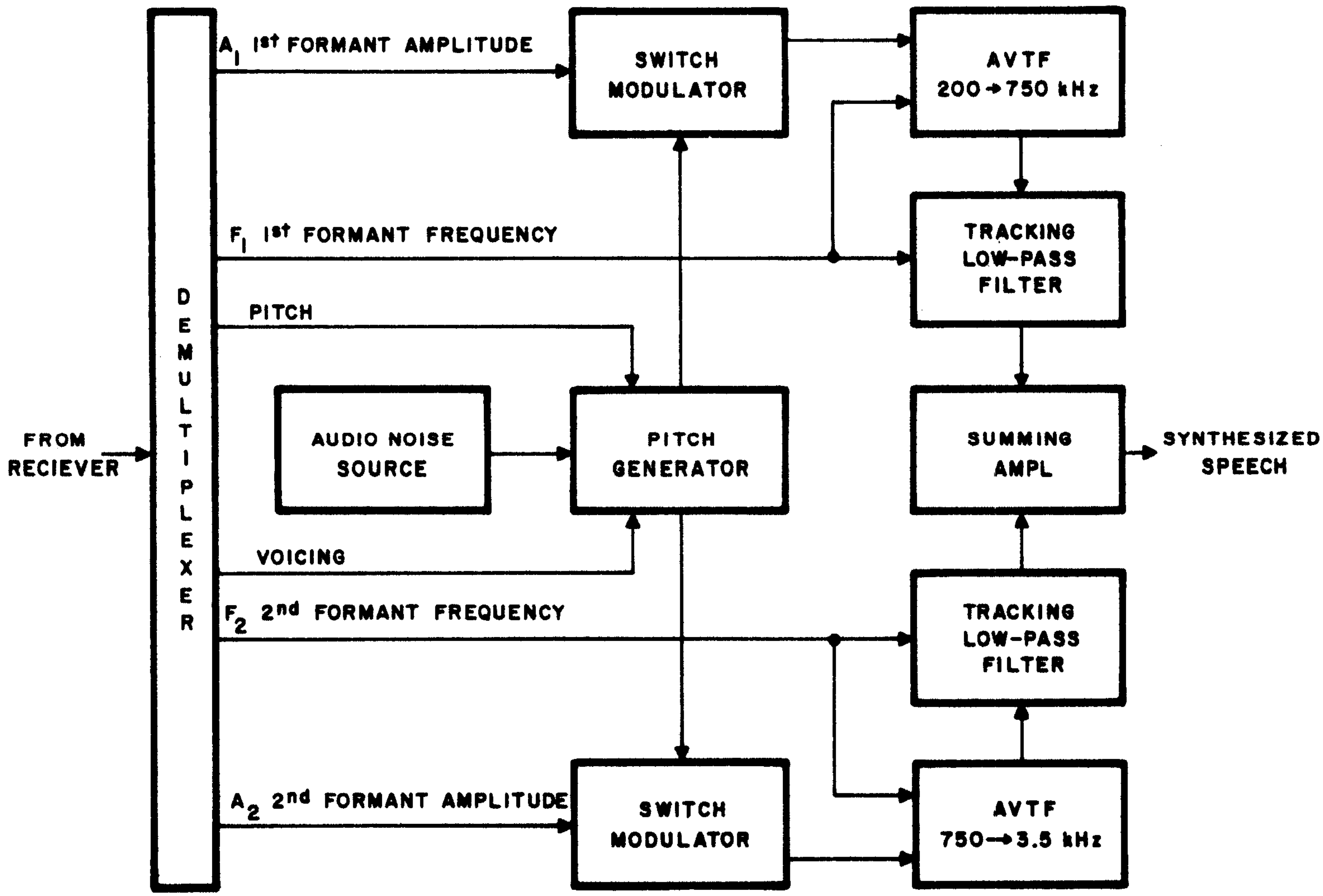

Figure 2-6. Synthesizer, Block Diagram

d. Thick-film or chip-and-wire microcircuits will be designed and used for certain high-use circuits.

e. Since the PAM multiplexer and demultiplexer are already 90 percent microminiaturized, no analysis of them will be made in this report. However, the component count, packaged volume requirements, and power dissipation is listed.

2.2.2 Overall System Block Diagrams

The overall system diagram consists of the Analyzer Block Diagram, Figure 2-5, and the Synthesizer Block Diagram, Figure 2-6.

2.2.3 Analyzer Block-by-Block Analysis

2.2.3.1 Analyzer Input Bandpass Filter

The input bandpass filters consist of two low-pass sections and two high-pass sections. Each section can be built by thick-film technique in a TO-5 can so that each bandpass filter would consist of four TO-5 cans. When these cans are mounted on a printed-circuit board the total size would be about 1.0 by 1.8 by 0.3 inches, or 0.54 in^3. These filters are within the current state-of-the-art, but would require developmental work to obtain the first yield of microcircuit bandpass filters.

2.2.3.2 Period Detectors

The period detectors would be constructed with integrated circuits where applicable, and discrete components would be used for the remaining circuitry, as shown in Figure 2-7.

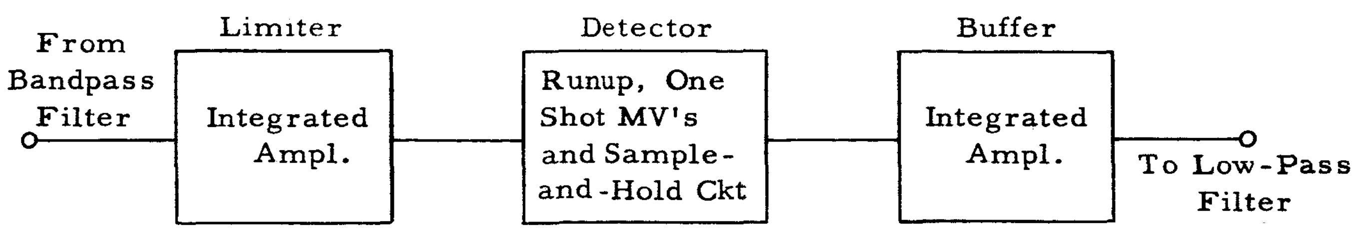

Figure 2-7. Period Detector

The circuits contained in the detector block are one-of-a-kind, and to miniaturize them would be most uneconomical. The detector block would therefore be built using discrete parts and would occupy about 1.5 in^3. The integrated amplifiers are TO-5 can types and, with their associated discrete components, their packaged volume will be about 0.5 in^3. Total volume for the period detectors will be 2 x (1.5 x 0.5) or 4 in^3.

2.2.3.3 20-Hz Low-Pass Filters

With present techniques the 20-Hz low-pass filters cannot be miniaturized to TO-5 cans. The best that can be done is to use a TO-5 size integrated amplifier with discrete filter components. Resultant size will be about 0.5 $in.^3$ per filter, with a total of 2.5 in^3.

2.2.3.4 Output Shapers

Integrated amplifiers, along with a small number of discrete components, will give the output shapers a volume of about 0.5 $in.^3$ each, or a total of 1 in^3.

2.2.3.5 Amplitude Detectors

The amplitude detectors will make use of integrated amplifiers in the circuit shown in Figure 2-8.

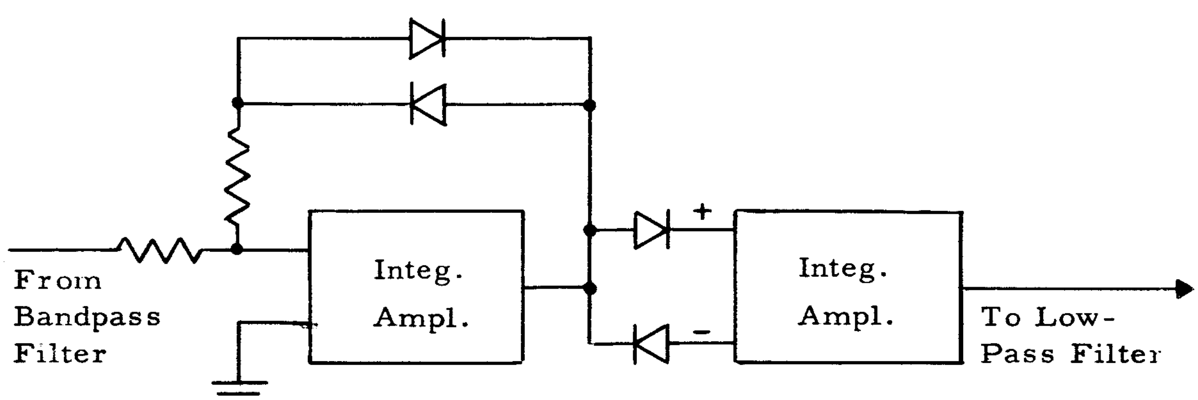

Figure 2-8. Amplitude Detector

Including the discrete components the volume of one amplitude detector will be about 0.5 in^3. Total volume for both detectors will be 1 in^3.

2.2.3.6 Pitch Extractor

The pitch extractor is a complex, iterative process requiring large capacitor values, and is therefore not adaptable to miniaturized construction. Its performance would be enhanced by the application of integrated amplifiers, however, and so they are used to maximum advantage as shown in Figure 2-9. Total volume for the pitch extractor would be about 9 in^3.

2.2.3.7 Voicing Detector

The voicing detector can be miniaturized by the partial use of integrated circuits, as shown in Figure 2-10.

The integrated circuits and their associated discrete parts would occupy about 1 in^3. The discrete component blocks would occupy about 3 in^3, for a total volume of 4 in^3.

2.2.3.8 Regulators

The +10 volt and -10 volt regulators would convert the 28-volt spacecraft supply utilizing integrated amplifiers; and with their associated discrete parts would occupy about 1.5 in^3 total.

2.2.3.9 Multiplexer

A total of 28 milliwatt modules are used in the analyzer multiplexer. These, and the few discrete parts used with them, can be packaged in about 2.5 in^3. The frequency source would be counted down from the 512-kc clock in the spacecraft, and can be built in 1 in^3 for total multiplexer volume of 3.5 in^3.

2.2.4 Total Analyzer Volume

The individual block volumes are:

Bandpass Filters	0.54 in^3
Period Detectors	4.0 in^3
Low-Pass Filters	2.5 in^3

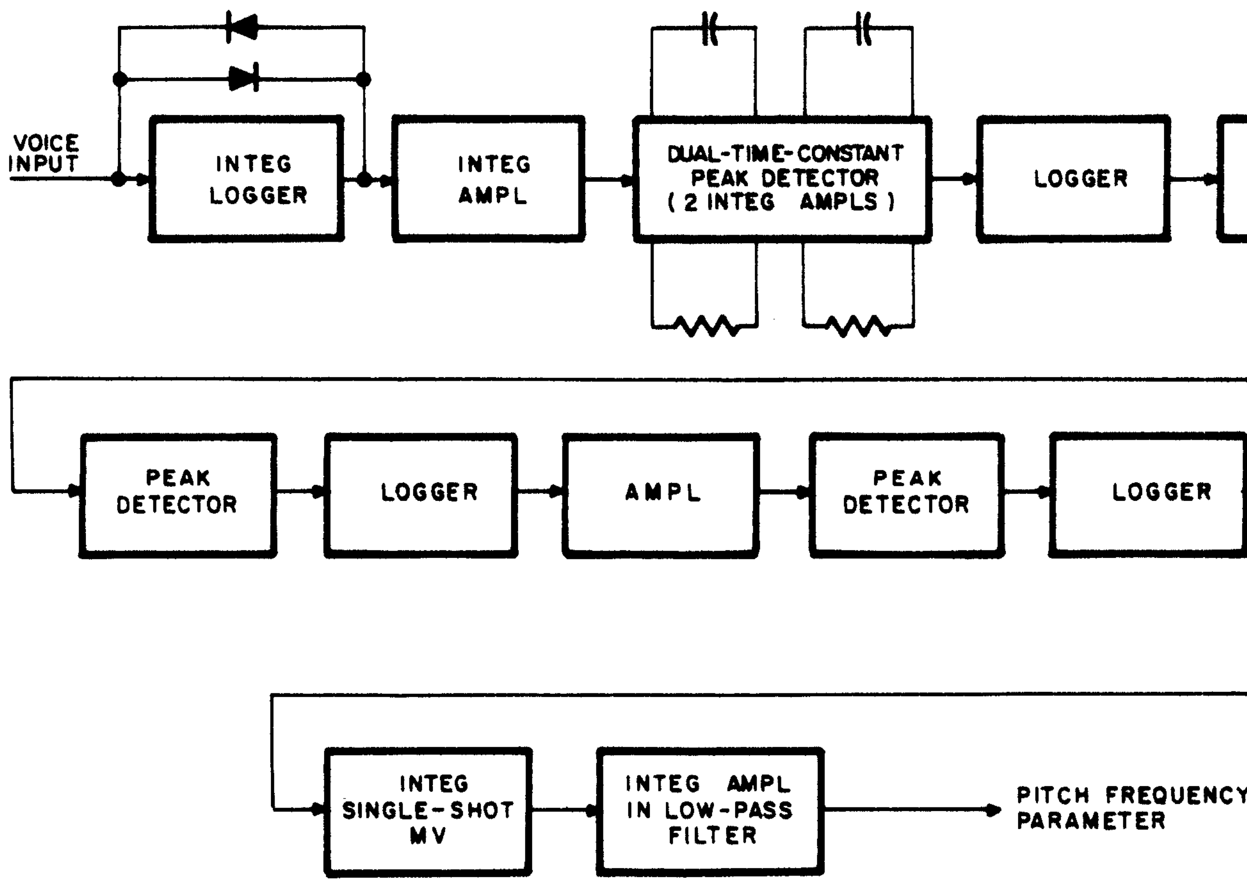

Figure 2-9. Pitch Extractor, Block Diagram

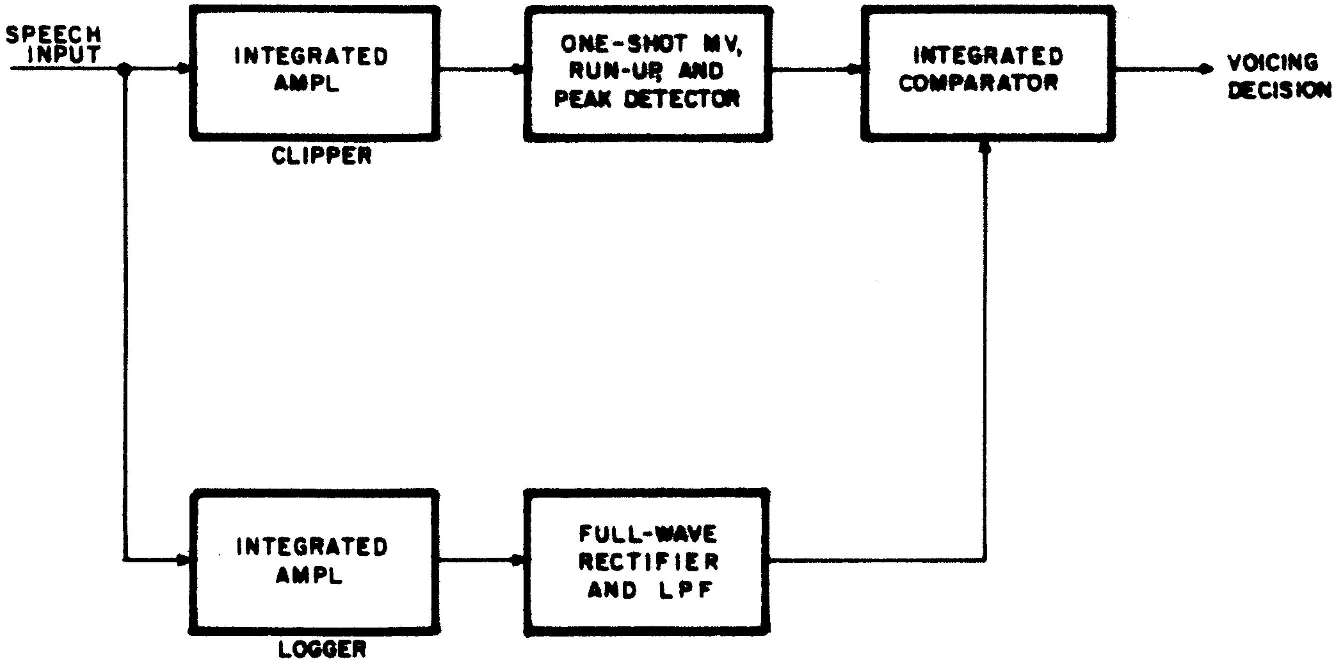

Figure 2-10. Voicing Detector

Output Shapers	1.0 in^3
Amplitude Detectors	1.0 in^3
Pitch Extractor	9.0 in^3
Voicing Detector	4.0 in^3
Regulators	1.5 in^3
Multiplexer	3.5 in^3
Total Module Volume	27.04 in^3

Assuming an 80 percent volumetric utilization, the projected total analyzer package volume would be 33.7 in^3.

2.2.5 Synthesizer

2.2.5.1 Noise Generator

A noise diode and an integrated amplifier will make up the noise generator. Volume will be about 0.5 in^3.

2.2.5.2 Pitch Generator

The pitch generator would employ a mixture of integrated circuits and discrete circuits, as shown in Figure 2-11.

The volume, including the discrete components in the driver amplifier and timing capacitors for the one-shot multivibrators, would be about 1.5 in^3.

2.2.5.3 Switch Modulators

The switch modulators would consist of an analog switch transistor followed by an integrated-circuit buffer amplifier. This would not result in size saving, but would increase performance.

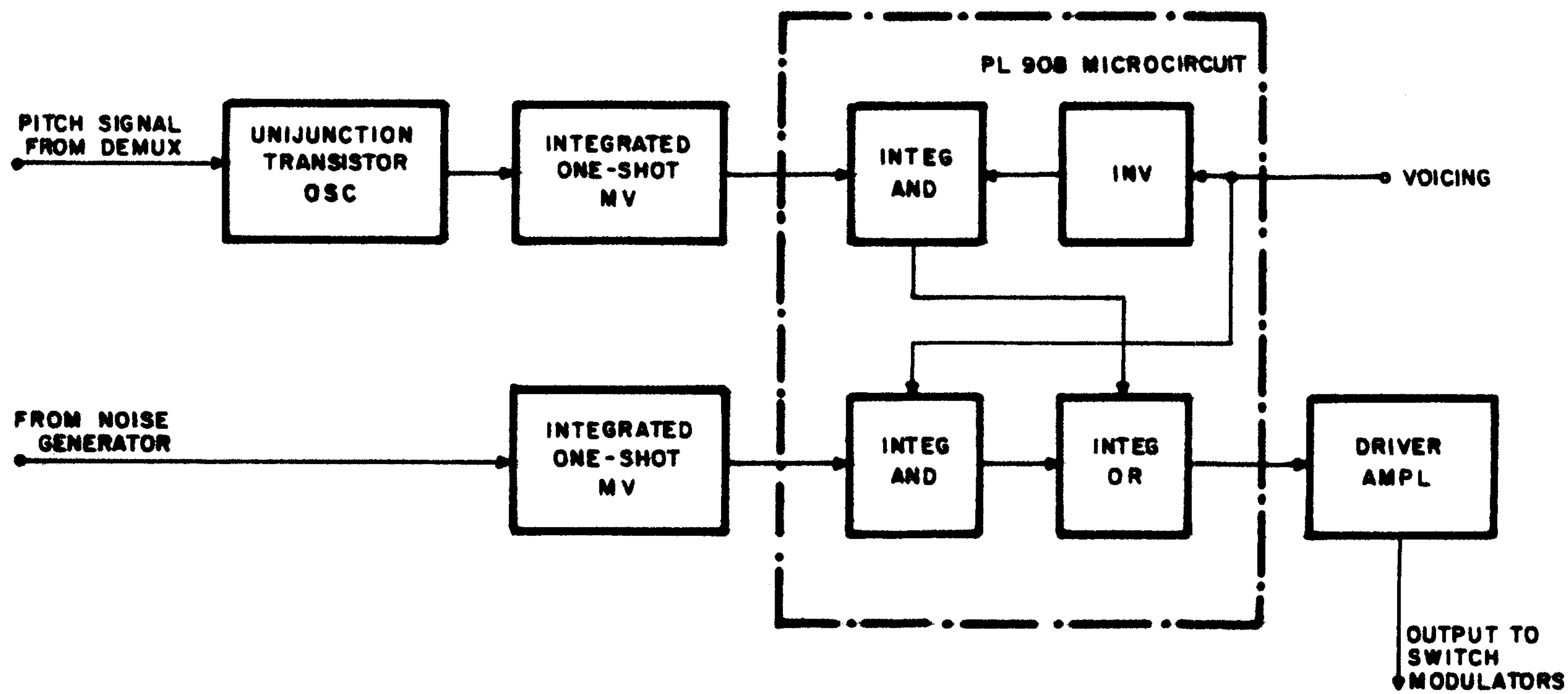

Figure 2-11. Pitch Generator

2.2.5.4 AVTF

The AVTF's would use one integrated amplifier and four discrete transistors. Because two transistors are matched FET's further miniaturization is probably not feasible. Volume of each AVTF would be about 1.5 in^3, for a total of 3 in^3.

2.2.5.5 Tracking Low-Pass Filters

These are very similar to the AVTF except that an integrated amplifier is not required. Total volume for both tracking filters would be about 2.5 in^3.

2.2.5.6 Summing Amplifier

The summing amplifier would consist of a single integrated amplifier and associated feedback components. It would occupy about 1 in^3.

2.2.5.7 Demultiplexer

The demultiplexer contains 102 TO-5 cans, which would occupy about 30 in^3. The frequency source would again be counted down from the 512-kc spacecraft signal, and would require about 1 in^3 volume.

2.2.6 Total Synthesizer Volume

In the synthesizer the projected individual block volumes are

Noise Generator	0.5 in^3
Pitch Generator	1.5 in^3
Switch Modulators	2.0 in^3
Tracking Filters	2.5 in^3
Summing Amplifier	1.0 in^3
Demultiplexer	31.0 in^3
Total Synthesizer Block Volume	38.5 in^3

Assuming an 80 percent volumetric utilization in the projected complete package gives a packaged synthesizer volume of 48 cubic inches.

SECTION 3

CONCLUSIONS

From the preceding discussion, it is concluded that an effective microminiature package is definitely feasible without major redesign of any block of the breadboard system.

The state-of-the-art in microcircuit techniques has progressed so rapidly that this system could be microminiaturized almost entirely from circuits that exist today and need no further development. The only major microcircuit development needed would be for the thick-film band-pass filters.

Figures 3-1 and 3-2 show block diagrams of one channel each of the microminiature analyzer and synthesizer. Note that 80 percent (16 out of 20) of the functional blocks are integrated circuits.

Therefore, it is concluded that the projected microminiature Narrow-Band Speech Communicator would have the following characteristics:

Volume:

Analyzer	33.7 in^3
Synthesizer	48 in^3
Total Volume	81.7 in^3

Size:

Depends on spacecraft configuration, but a typically feasible one would be 3" x 4-1/2" x 6".

Weight

Projected from similar microminiature Vocoder volumes and weights:

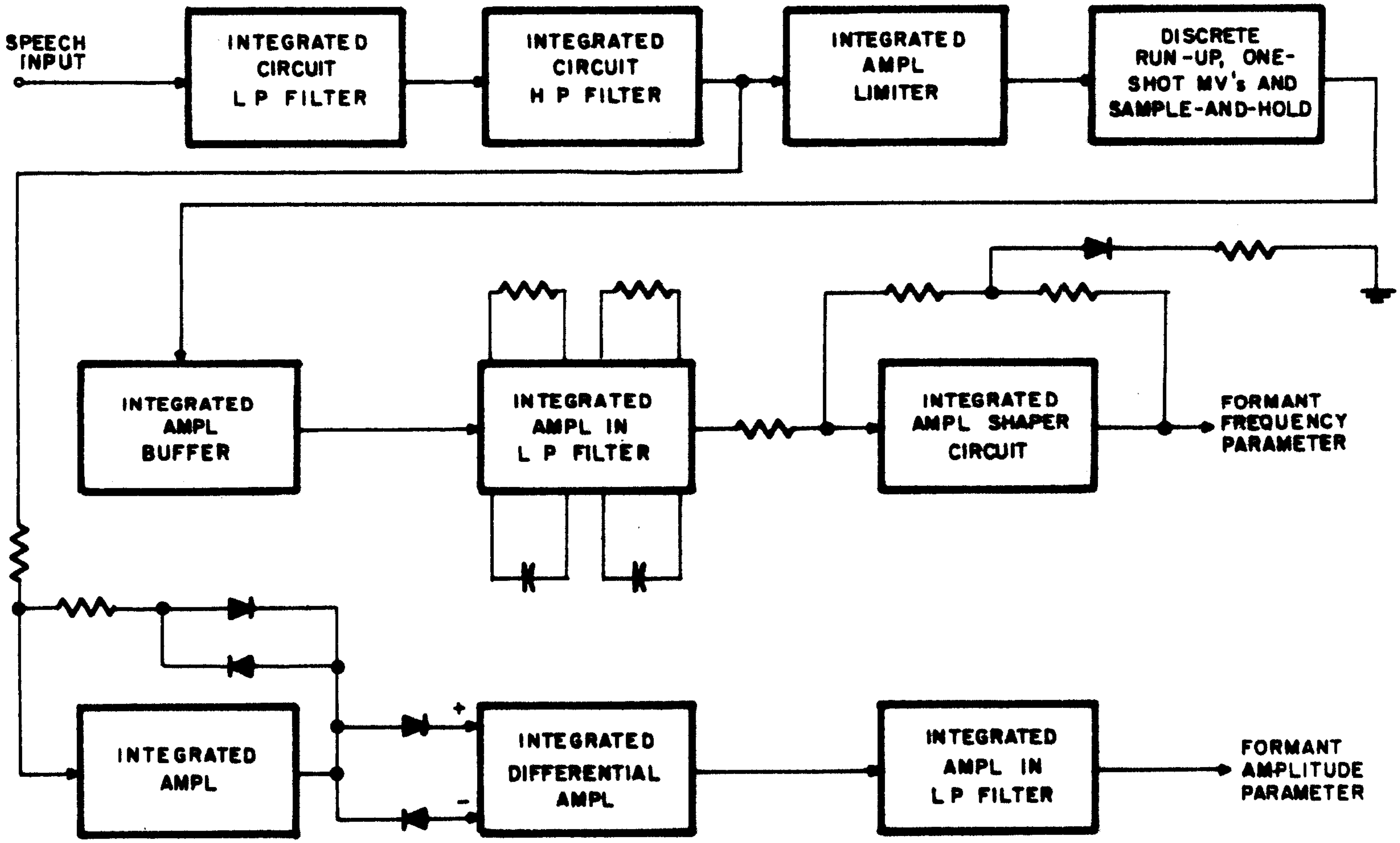

Figure 3-1. Block Diagram of One Channel of Formant Analyzer

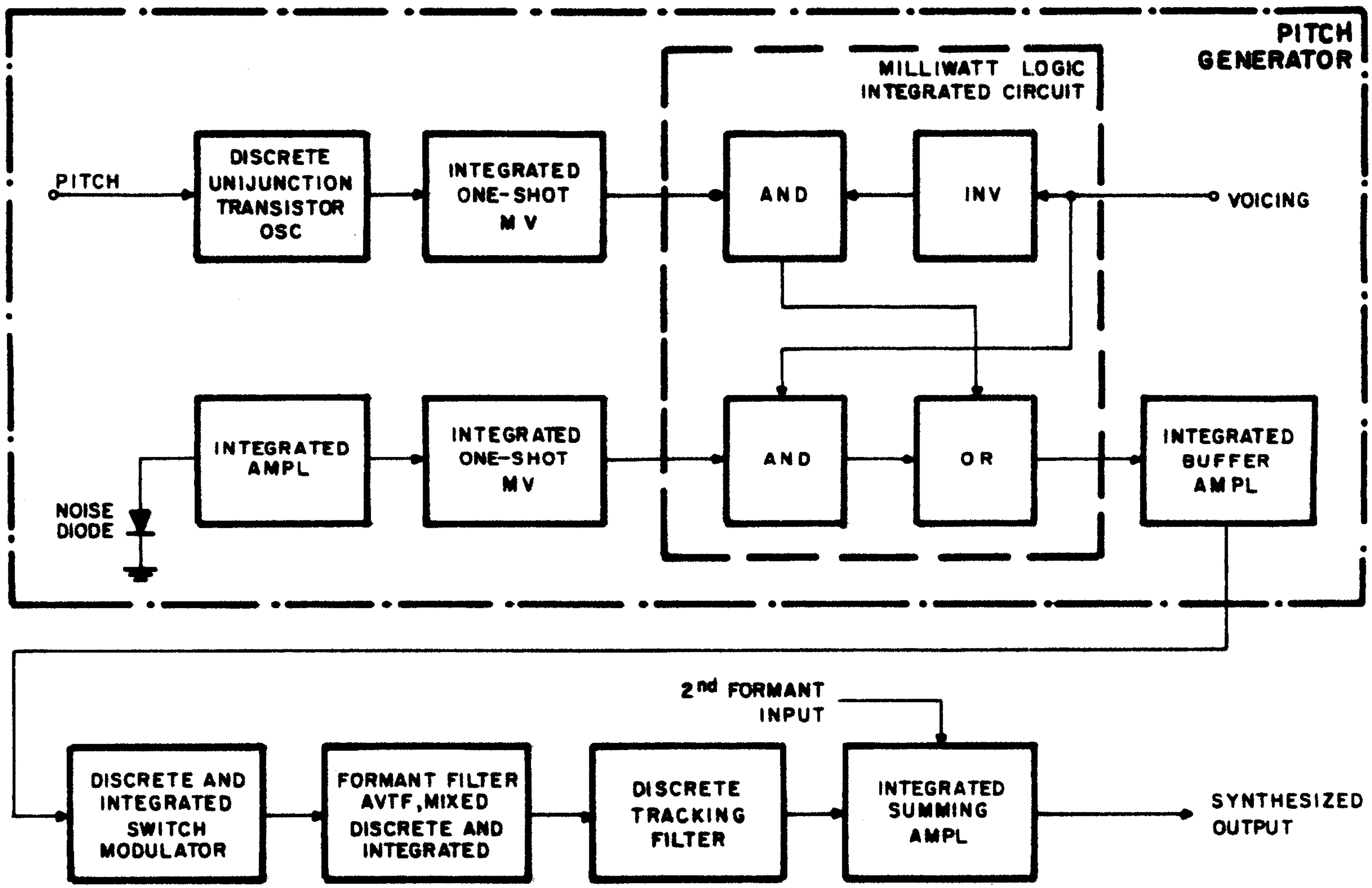

Figure 3-2. Block Diagram of One Channel of Synthesizer and Pitch Generator

Analyzer	4.1 lbs.
Synthesizer	5.9 lbs.
Total	10 lbs.

Power Consumption:

Analyzer:

Discrete analyzer circuits	0.3 watt
Integrated analyzer circuits (34 x 0.051) =	1.73 watts
Multiplexer integrated circuits	1.0 watt
Total	3.03 watts

Synthesizer:

Discrete synthesizer circuits	0.3 watt
Integrated synthesizer circuits (10 x 0.051) =	0.51 watt
Demultiplexer integrated circuits	1.0 watt
Total	1.81 watts

Total Equipment: 4.84 watts