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by

W. H. Ko
E. Yon
W. Thompson

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I. Abstract

The purpose of this project is to develop techniques for fabrication of multiple-channel, physiologically implantable, telemetry systems. These systems must be able to telemeter a wide range of physiological signals. This report covers the second semiannual period from September 1966 to March 1967.

A system design has been formulated and tested. The system uses a PAM-FM, time-division multiplexed format and is sufficiently flexible to allow the use of any number of channels up to ten with a total information bandwidth of up to 20 KHz.

Tests have been made on a prototype system having one sync channel, two 3 KHz channels for electrical signals, and one strain gage channel with a 200 Hz bandwidth. The noise levels for the 3 KHz were under 2% of full scale; for the strain gage channel, the noise level was under 1% of full scale. The total crosstalk between the channels was much less than the noise level and thus not measurable.

An implant test was made in a dog of a transmitter using the same RF circuitry as the final unit. The transmitter had one subcarrier oscillator whose frequency was controlled by a strain gage. Standard miniature components were used throughout. The unit, which was powered by mercury batteries with a predicted lifetime of 150 hours of operation, was activated by a magnetic switch from outside the animal.

This system was implanted in a dog at the Pharmacology Department of the University of Michigan on February 23, 1967 and was still functioning well six weeks later. There was no external evidence of any infection in the subject.

Equipment has been purchased or constructed with funds from this grant and other supports to be used to fabricate the circuitry in hybrid integrated circuit form. Hybrid circuitry is presently being fabricated, and is being used in associated projects within our group.

Studies have been made of several types of frequency-modulated oscillators. A theoretical study has been made of the optimum method of modulation applicable to the multiple-channel system. Results indicated that double-sideband, suppressed carrier AM was theoretically optimum. A study was also made of power supply methods. The use of nickel-cadmium batteries recharged by RF induction was selected for initial study.

II. Background

The final system must be suitable for implanting in small animals, as a dog or a monkey, and capable of simultaneously telemetering several of the commonly measured physiological variables. These requirements set up several guide lines for the implanted package.

The circuitry in the implant, or transmitter system, must be simple and non-critical. This is necessary from the standpoint of miniature construction as well as for reliable operation in a completely remote (from the operator) location. This rules out sophisticated, high-performance, circuitry from size as well as from maintenance considerations as any balancing or adjusting is impossible.

Size considerations also dictate that the circuitry be suitable to fabrication in integrated circuit form. The use of standard discreet components would make the circuitry too bulky for an implant.

The circuitry must require a minimum of power from its power supply. Batteries will be used for the power supply and will have a limited lifetime. Since the batteries are not easily replaced they must be used economically to give a long useful life to the system. Thus, battery drain must be minimized. This is necessary even if rechargeable batteries are used, as it is desirable to recharge them as infrequently as possible.

The system must accept direct electrical signals picked up from electrodes, must accept resistive sensors (as thermistors and strain gages), and be adaptable to other types of transducers. The system must be flexible in the number of signals able to be processed, and expandable up to ten channels.

The RF link for the system must be capable of transmitting the signal from the implant to the external monitoring system. The noise level of the link, which includes the implanted RF transmitter and the external receiver, must be adequate to allow 1% or lower noise levels in the individual channels. The range of the system should be at least 20 feet in an open room.

The results of a study of several multiplexing systems indicated that a pulse-amplitude-modulated, time-division multiplexed system with an FM RF link was the most suited to the above requirements at the present time. A PAM-FM system has the simplest circuitry of the time-division multiplexed systems. It uses no bulky inductances and very few capacitances which makes it superior to an FM-FM system from the integrated circuit fabrication consideration.

Another, and very important advantage of a PAM-FM system is in power supply economy. Circuitry can be designed to require power only when actually being used to process information and turned off when not needed. This allows several channels to operate with the same power drain as a single channel in continuous operation. In this way, additional channels would not increase the power supply drain.

Additional channels can be inserted into the PAM format with only the addition of the circuitry pertinent to that channel and without any other changes in the implant package circuitry.

The PAM-FM system is easily designed for integrated circuit fabrication. The system can be built, except for the RF unit, with very few capacitances and no inductances. The circuitry uses non-critical resistor and transistor chips and a few monolithic differential amplifier chips.

III. Progress Made From October 1966 to February 1967

During this period the design of the system has been finalized. Circuitry for the transmitter, or implant portion of the system, and for the demultiplexing system have been designed, constructed, and tested. An implant has been made to obtain some preliminary information about the RF link, and fabrication facilities have been put into operation.

A. Transmitter System

The system which has been developed is given in block diagram form in Figure 1. The transmitter consists of signal conditioners (amplifiers), a multiplexing gate, a ring oscillator to drive the multiplexing gate and to gate the power supplies to the signal conditioners, a frequency-modulated oscillator, and a power pack or power supply. The transmitter also contains sources of sync and calibration pulses for the composite PAM signal.

The individual signal conditioners are dependent on the signal to be processed by that channel. Direct electrical signals require differential amplifiers. Resistive sensor pickups require a bridge followed by a differential amplifier. Other signal sources would require signal conditioners tailored to their specific needs. The outputs of the signal conditioners are at a common level and amplitude to feed the multiplexing gate.

The power supply to each signal conditioner is gated so that the individual conditioners are turned on only when it is actually being used. This saves on power supply drain as well as in virtually eliminating any crosstalk generation in the transmitter.

The multiplexing gate connects each channel, including the sync and calibration channels, in sequence to the RF circuitry. The frequency of the RF oscillator is modulated by the series of pulses from the channels.

The ring oscillator supplies the gating control signals for the power supplies to the signal conditioners and for the multiplexing gate. The ring oscillator contains an automatic reset feature to start itself and, in case of malfunction, restart itself.

The power supply will be either mercury batteries or rechargeable nickel-cadmium batteries. A magnetic switch will be used to activate the transmitter. In the case of the rechargeable batteries, an RF induction recharging method will be used.

B. Receiver and Demultiplexing Circuitry

An FM receiver with an FM frequency response of 300 KHz is required for the 20 KHz total information bandwidth system. Lower total information bandwidth systems would require correspondingly lower FM frequency responses.

The output of the FM receiver must be demultiplexed, or directed into the proper channels. Figure 2 gives the block diagram for demultiplexing circuitry for the PAM-FM system.

The composite PAM waveform loses its DC component as it passes through the RF link. It is very difficult to preserve DC information on an FM carrier directly. This must be restored for the demultiplexing circuitry The clamping circuit restores the level of the received composite PAM by locking the sync pulse, a fixed maximum amplitude pulse, to a fixed level.

Since the gain of the RF link and of the video amplifier in the receiver may vary, it is necessary to apply automatic gain control (AGC), to the incoming composite PAM. This is done in the AGC circuit by adjusting the gain until the difference between the maximum height (sync) and minimum height (calibration) pulses is a constant.

The demultiplexing circuitry contains a ring oscillator similar to the one in the transmitter. The demultiplexer ring oscillator is synchronized with the transmitter each time a sync pulse occurs. Each time the ring oscillator switches channels, the sample window generator produces, a fixed time later, a narrow sample command signal. The output of these two circuits combine to activate the demultiplexing gates.

When activated, the sample and hold circuits charge a capacitor to the value of the composite PAM at the instant of command. This capacitor holds charge until the next time that channel's time occurs, at which the capacitor's voltage is modified to correspond to the new value of PAM. A low-pass filter following the sample and hold circuit removes the components of the sampling frequency and provides the filtered channel output.

The next section deals with actual waveforms present in the demultiplexing circuitry for a four-channel system used for evaluating the performance of the overall system design.

C. Circuit Design and System Evaluation

The circuitry used in the transmitter and in the demultiplexing system have been designed and built. Their design is discussed in detail in an

Internal Report of the Solid State Electronics Laboratory.

A four-channel system has been constructed and evaluated to determine system performance. This system had two 3KHz bandwidth channels for direct electrical signals, a 200 Hz bandwidth strain-gage input channel, and a sync channel. All the elements of the block diagram of Fig. 2 were included except the AGC circuit.

Fig. 3 gives the composite PAM waveforms at the output of the clamping circuit for this system. Fig. 3a gives an unmodulated PAM while the waveform of Fig. 3b has about 1 volt peak-to-peak modulation at 190 Hz on channels one and three. The maximum amplitude pulse is the sync pulse. The top of this pulse is clamped to zero volts. Channel one, two and three then follow in sequence, with channel two having a strain gage bridge connected to its input.

The clamp and sample windows provide for action of the clamping and demultiplexing gate circuitry respectively after all transients have died out due to the switching between channels. This is necessary to eliminate crosstalk since any transient has a memory of the previous channel. Fig. 4 shows the timing of the clamp and sample windows.

The outputs of the ring oscillator are shown in Fig. 5. This shows the composite PAM along with the ring oscillator outputs corresponding to channels 1, 2 and 3. These outputs, along with the sample window, control the demultiplexing gates (sample and hold circuits).

Noise level and crosstalk performance tests were made on this system. The results of these tests are given in Fig. 6. Fig. 6a shows the noise levels for the three channels, 1, 2, and 3, from top to bottom. The calibration is 20 mv/cm vertically and 5msec/cm horizontally. Fig. 6b shows the effect on channel 2 of large modulation amplitudes in channels 1 and 3. The modulation in channel 1 is about 1.6 volts peak-to-peak at 100 Hz. There is no perceptible change in the output of channel 2 for changes of zero to maximum modulation on channels 1 and 3. An AC VTVM connected to channel 2's output during these tests read about 2 mv independent of modulation levels on 1 and 3.

Only the demodulation circuitry of channel 2 has been optimized for reducing noise level at the time of these photographs. Other tests have shown noise levels for these channels can be reduced by a factor of two, indicating further improvements can be made in the design. These tests have been made on a system with a maximum information bandwidth of 20 KHz. A lower maximum bandwidth capability, with the accompanying lower sampling rate, would give better noise characteristics.

D. Implant Test

A test transmitter has been implanted in the intestinal region of a dog. This transmitter had a frequency-modulated subcarrier, which was controlled by a strain gage, and a frequency-modulated RF oscillator. The strain gage was sutured onto the lower end of the dog's stomach to telemeter contractile-force information from the stomach.

This transmitter used the same RF circuitry that is planned for the multiple-channel system. This allowed an evaluation of packaging and implant techniques as well as evaluaton of the RF link. The unit was powered by mercury batteries having a predicted lifetime of approximately 150 hours and activated by a magnetic switch upon external command.

The system was monitored daily for 6 weeks and gave very good results. The system was usable with the dog performing normal physical activities. There was no sign of any infection or reaction due to the transmitter during this period. There was no noticeable erratic circuit behavior indicating minimal leakage of body fluids into the transmitter package.

Fig. 7 gives the circuit diagram for the test transmitter. This circuit uses a phase-shift oscillator as the subcarrier oscillator. The phase-shift characteristic is modified by the strain gage bridge and thus the strain-gage controls the frequency of the oscillator. The output of the subcarrier frequency modulates the RF oscillator which radiates to the external receiver.

Fig. 8 gives the demodulator which was developed for this system. The Fairchild μA710 circuit is a hysteresis comparator which generates a rectangular wave from its input signal. This wave then triggers the μL923 integrated circuit flip-flop. The μL923 is then reset by a unijunction timing circuit. Thus a fixed length pulse is generated once each cycle of the input. These pulses are integrated by the low-pass filter. The output of the filter is compared with a reference level and amplified by the μA702. Since the normal frequency of the signals in the stomach was a few cycles per minute, the μA702 amplifier was given a 10Hz bandwidth to cut out high frequency noise from other sources.

Fig. 9 shows typical data sample from this system. This record is very similar to a record taken from a wired system. This record was made about two weeks after the implant was made.

E. Fabrication Facilities and Techniques

The finished transmitter package will be constructed with hybrid integrated circuits. The circuitry will be broken down into units of a maximum of 10 to 15 resistors and transistors each. These units will be built in flatpacks. Capacitances will be added externally. The flatpacks will be interconnected to fabricate the complete system. The RF circuitry will require several capacitors and an inductor in addition to one flatpack of circuitry.

The equipment and supplies required for hybrid circuit fabrication have been obtained. The equipment and fabrication techniques are being put into operation. The materials are being tested and used in practice runs with the fabrication equipment.

The circuits for the flatpacks are built on ceramic substrates. These substrates have silk-screened gold patterns fired into their surfaces. Transistors and resistors in discreet chip form are bonded to the gold patterns. Individual components are interconnected with .001" diameter gold or aluminum wires. Final connections are made from the substrate to the leads of the flatpack.

All equipment and processes required for the fabrication of ceramic substrates are presently operational. Test patterns have been made to evaluate the techniques. Many of these patterns are currently in use on other projects.

An existing bonder was modified to operate as a eutectic diebonder and is now in operation. An ultrasonic wire bonder was purchased to use in making the wired interconnections. A thermocompression bonder modification kit is on order to make the unit more versatile. The bonder's operation is currently being evaluated in conjunction with the circuitry required for this project. It has also been used to fabricate circuitry for other projects in our group.

A probing system and a curve tracer have been purchased and put into operation to test the chip components prior to their use in the fabrication of circuits.

Facilities are being put into operation for the manufacture of diffused silicon resistors and of field effect transistors. This program included the purchase of a mask-alignment system for exposing photo-sensitive resists, used to delineate the diffuse silicon devices. A photo-resist spinner and ovens for baking the resist have also been purchased and put into operation. Furnaces have been set up for the necessary diffusion steps. A scribing system has been purchased and put into operation for use in breaking the wafers into individual components.

IV. Associated Projects

Studies dealing with portions of the overall project have been made. These include a study of frequency-modulated oscillators, a theoretical study of the optimum RF link for the system, and a study of possible power supply methods.

A. Frequency-Modulated Oscillators

A study of frequency-modulated oscillators has been made to evaluate various types which possibly have application to this system. Since a stable carrier frequency is highly desirable, crystal-controlled oscillators were studied. It is possible to vary the frequency of a crystal oscillator by varying the external capacitance presented to the crystal. The results of studying several circuits of this type showed that in order to obtain deviations of 0.01%, very critical adjustments were necessary. Also, bandwidths obtained were too small for the multi-channel system. Phase modulation of a crystal oscillator was also studied. This method would require too extensive circuitry for the proposed integrated circuit construction.

Another possibility investigated was the use of a phase-locked loop in the transmitter to stabilize the carrier frequency. This method hasn't shown promise since it is difficult to obtain sufficient isolation between the reference oscillator and the voltage controlled oscillator. There are also problems in obtaining sufficient information bandwidth.

In the course of these investigations it was noted that, for the deviation ratios necessary for the required bandwidth for the multi-channel system, the FM improvement over AM was very small or non-existent. For this reason, and for the carrier stability offered by a crystal-controlled oscillator, an amplitude-modulated crystal-controlled oscillator was built and tested. This PAM-AM system gave good results and had more than adequate bandwidth.

Non-crystal-controlled transistorized oscillators, frequency-modulated by varacaps, were also constructed and tested. The PAM-FM circuits so tested gave good results with the exception that the frequency of oscillation was influenced by such factors as power supply variations and by the proximity of external objects. It remains to test these frequency varying effects for this circuit in integrated circuit packaging. Proximity effects should be minimized by the miniature packaging and by the use of a power amplifier stage following the oscillator to minimize loading effects.

The crystal-controlled PAM-AM circuit and the non-crystal-controlled PAM-FM circuit will be further evaluated and compared on the basis of performance and ease of construction.

An M.S. thesis resulted from this study of oscillators and modulation. (1)

B. Theoretical Design of an Optimum RF Link

The theoretical design of a specialized communication link optimized for the PAM format for the multiple-channel system was carried out. This study compared several types of communications links on the basis of the requirements of the multi-channel system. Bandwidth requirements, error probabilities, carrier stability and noise performance were among the criteria considered. The optimum mode of communication chosen was double sideband, suppressed carrier AM. Following this choice, a theoretical design for the communications link was worked out.

This type of system has the advantage of having a crystal-controlled carrier and simple circuitry in the transmitter and uses readily available integrated circuits, along with the crystal, the inductor, and the bypass capacitors. This system has a better predicted noise performance than a comparable FM system.

This system requires a demodulation scheme which is not available on standard telemetry receivers. For this reason a complete system hasn't been tested; however a transmitter has been built which has been tested.

This study was performed as a senior Electrical Engineering Lab project at Case.(2)

C. Power Supply Methods

A study was made of possible power supply methods. The use of rechargeable batteries recharged by the use of RF induction was studied. Several types of batteries and charging methods were studied. Nickel-cadmium batteries were selected and a charging-control circuit was developed.

Charge-discharge characteristics of the batteries were studied. Charge-discharge characteristics were obtained experimentally for continuous cycling over a period of several weeks for a pair of batteries.

Methods of charging were studied. It is desirable to charge the batteries to full capacity in as short a time as possible. By combining constant voltage and constant current charging, the charging time necessary was reduced from the manufacturer's recommended 14 hours to 8 hours or less.

RF powering was studied and the necessary coupling coils were constructed and tested. The charging circuit, including pickup coil and constant voltage plus constant current source, was built and used to successfully charge a 6 volt, 150 ma. hr. nickel-cadmium battery pack in an 8 hour period. The dimensions of the present pickup coil are too large for an implanted unit and further work is necessary in this area.

Exploratory investigations were also made on the possibility of using a biological battery. Platinum-black and silver-chloride electrodes were used as anodes while zinc, steel, and aluminum were used as cathodes. Ringer's solution was used as the electrolyte. The results indicated that the maximum power density available is 200 microwatts per square centimeter for the experimental setups investigated.

This study on power supply methods results in an M. S. thesis.(3)

V. Estimated Schedule

The design of the implant package has been proven satisfactory so that the packaging of some of the circuitry in integrated circuit form can proceed. The circuitry of the implant package will be reduced to units and these units fabricated in flatpacks.

A system using four strain gages and an electrical signal, EKG, or EMG, will be built and implanted by September, 1967. By this date, the demodulation circuitry will be built in printed circuit form to allow for ease of expansion to different numbers of channels. Modifications will be made in the demodulator circuitry during this same period to increase the reliability and performance of the overall system.

References

1. Stevens, Grady, An Examination of Transistor F-M Transmitters Suitable for Multiplex Bio-Telemetry, M. S. Thesis, Case Institute of Technology, November, 1966.

2. Jagodnik, Anthony John, Jr., The Theoretical Design of an Optimum Communication System for Biological Telemetry Experiments, Senior Electrical Engineering Lab Report, Case Institute of Technology, January, 1967.

3. Noel, Bruce, Power Supply Problems in a Biomedical Telemetry System, M. S. Thesis, Case Institute of Technology, November, 1966.

4. Thompson, W. L., Circuit Design and Evaluation of Four Channel PAM-FM Telemetry System. Solid State Electronics Lab, Internal Report, Case Institute of Technology, May, 1967.

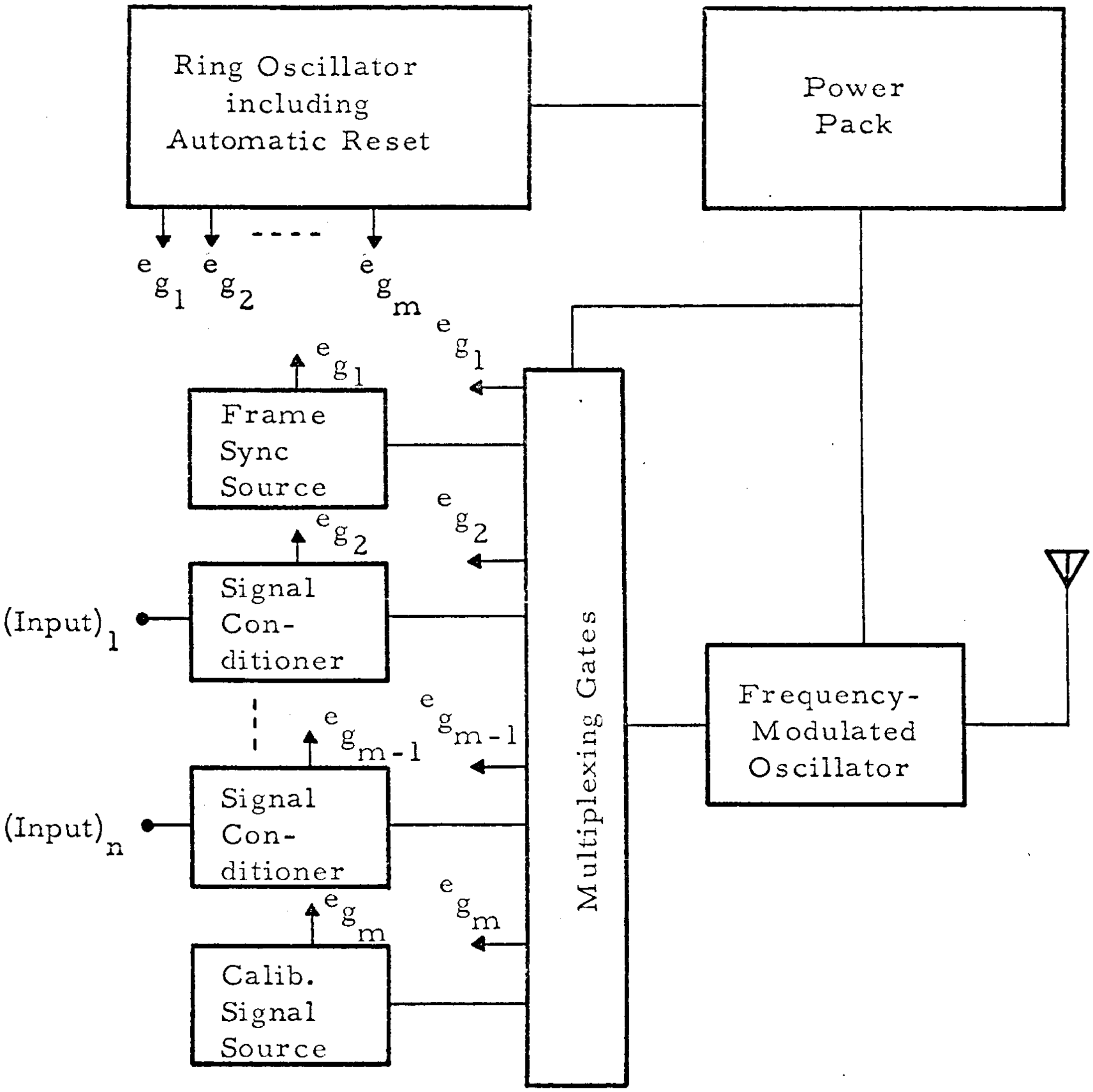


Figure 1. Block diagram of transmitter.

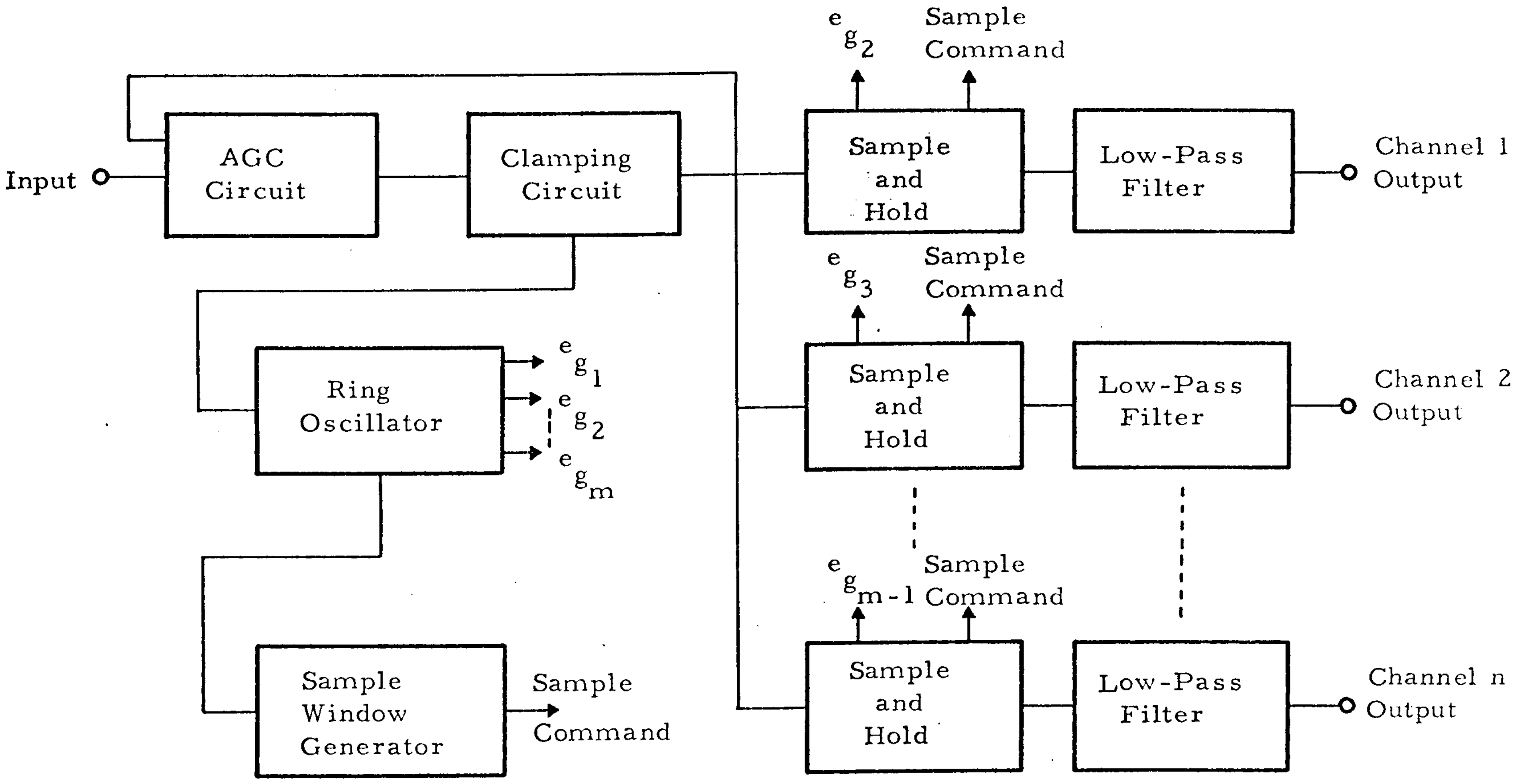
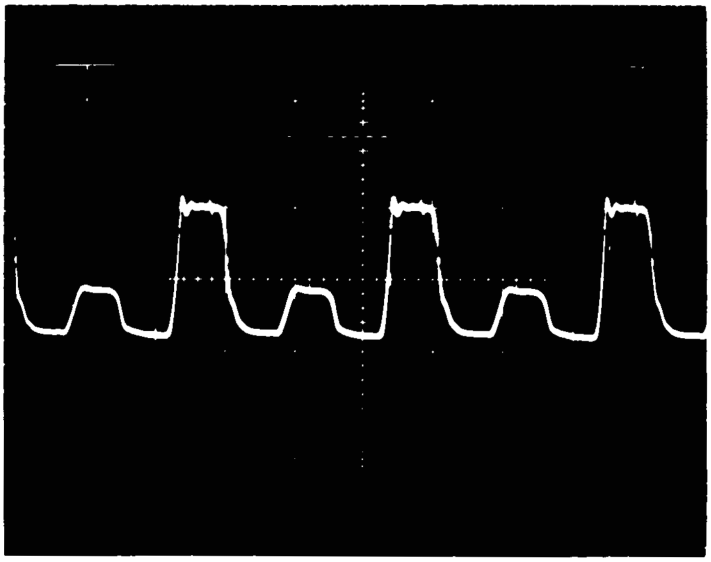
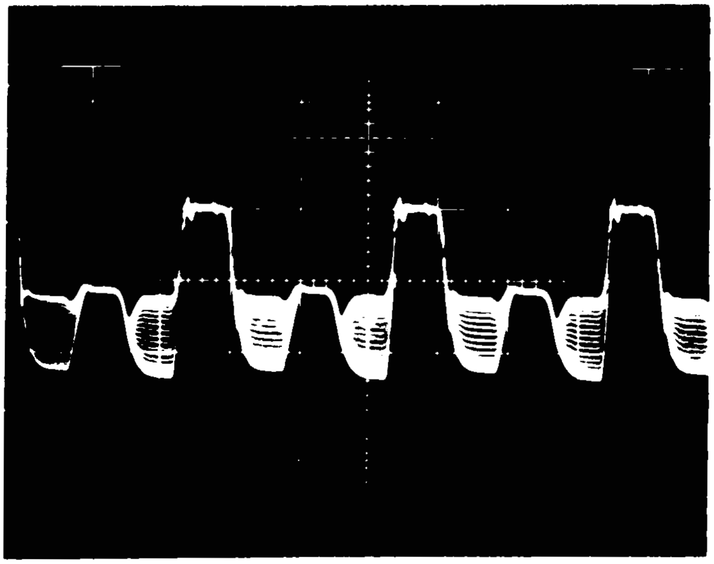


Figure 2. Block diagram of demultiplexing system.



a.

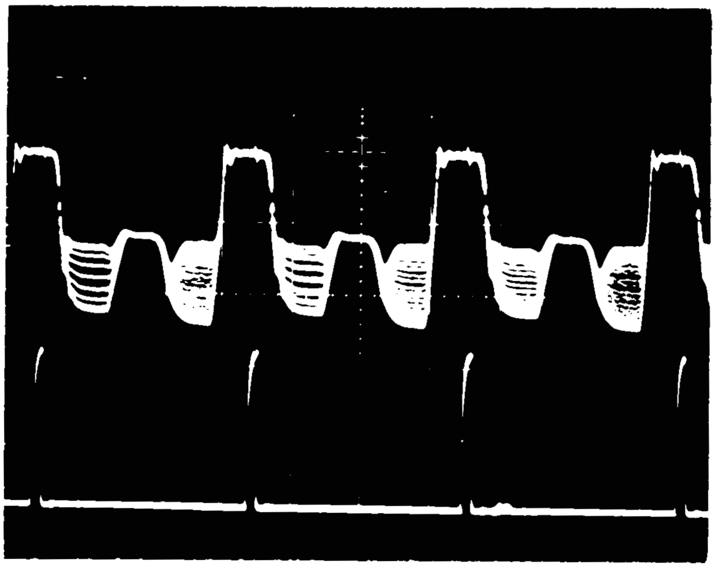


b.

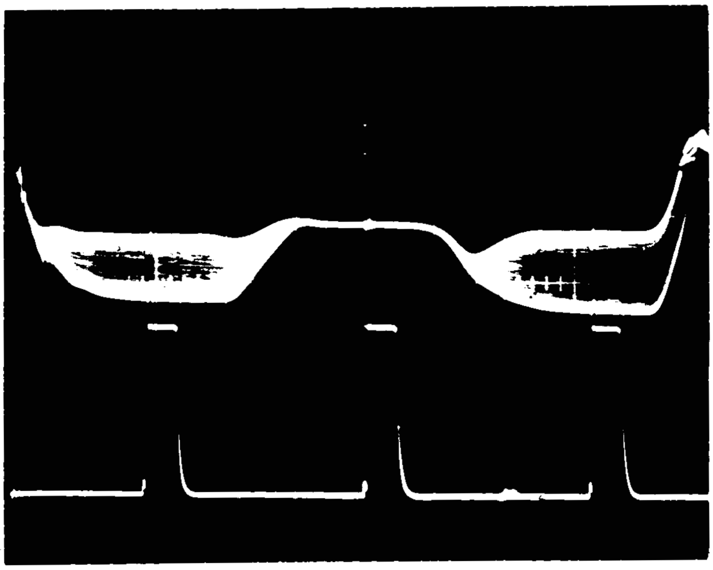
Figure 3. Composite PAM Waveform at Output of Clamping Circuit

a. Unmodulated

b. Modulation on Channels 1 and 3



a.



b.

Figure 4. Composite PAM With Clamp and Sample Windows

a. Clamp Window
b. Sample Windows

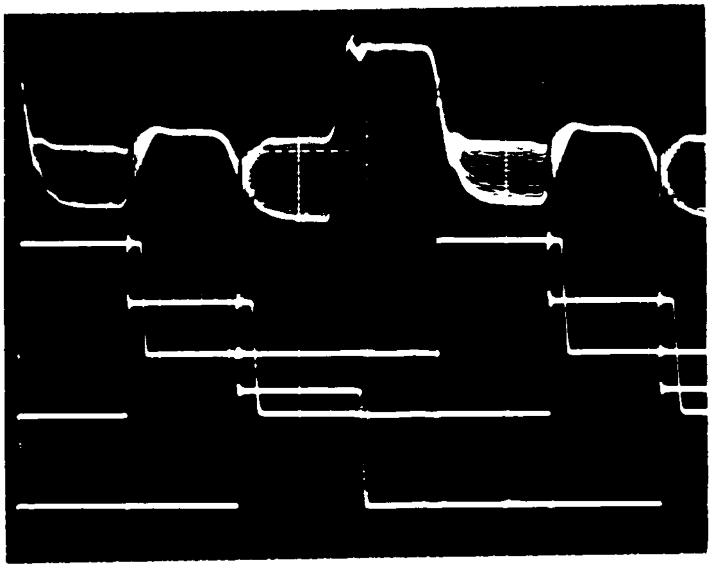
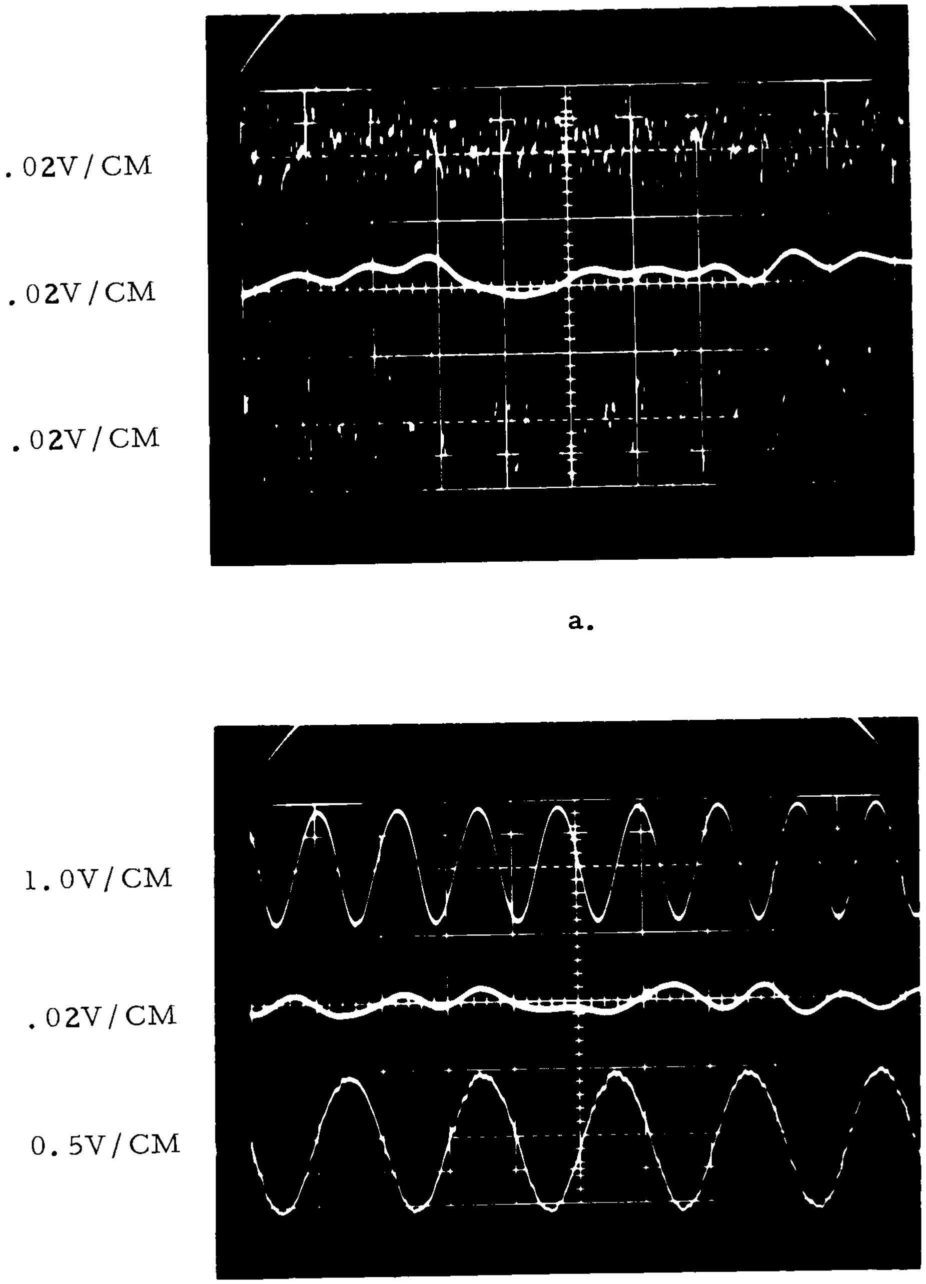


Figure 5. Composite PAM With Ring Oscillator Outputs



b.

Figure 6. Noise and Crosstalk

a. Channel's Noise Levels

b. Crosstalk into Channel 2 for Channels 1 and 3 Modulated to Full Scale

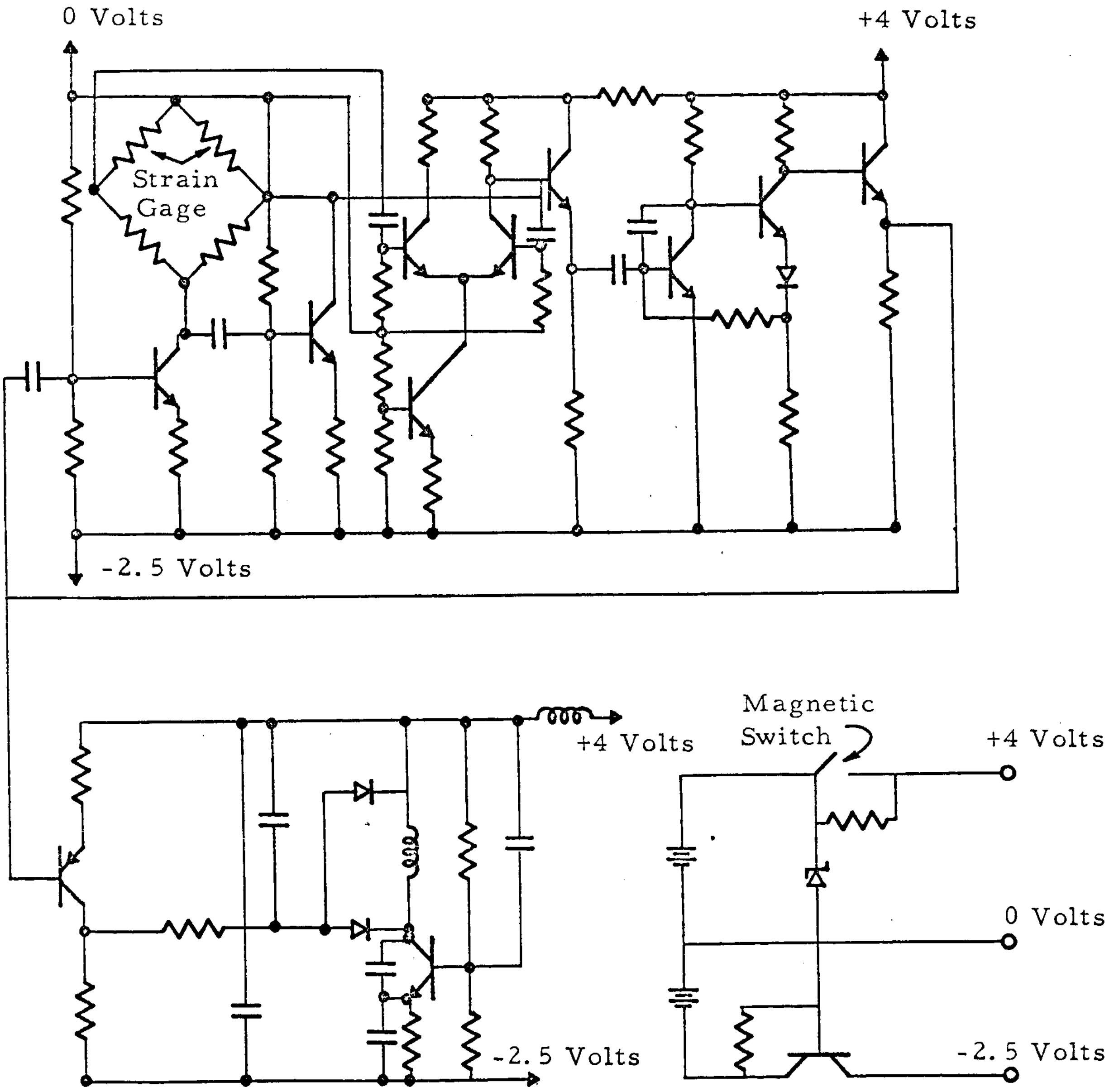


Figure 7. Circuit diagram of FM-FM telemetering system for strain gage.

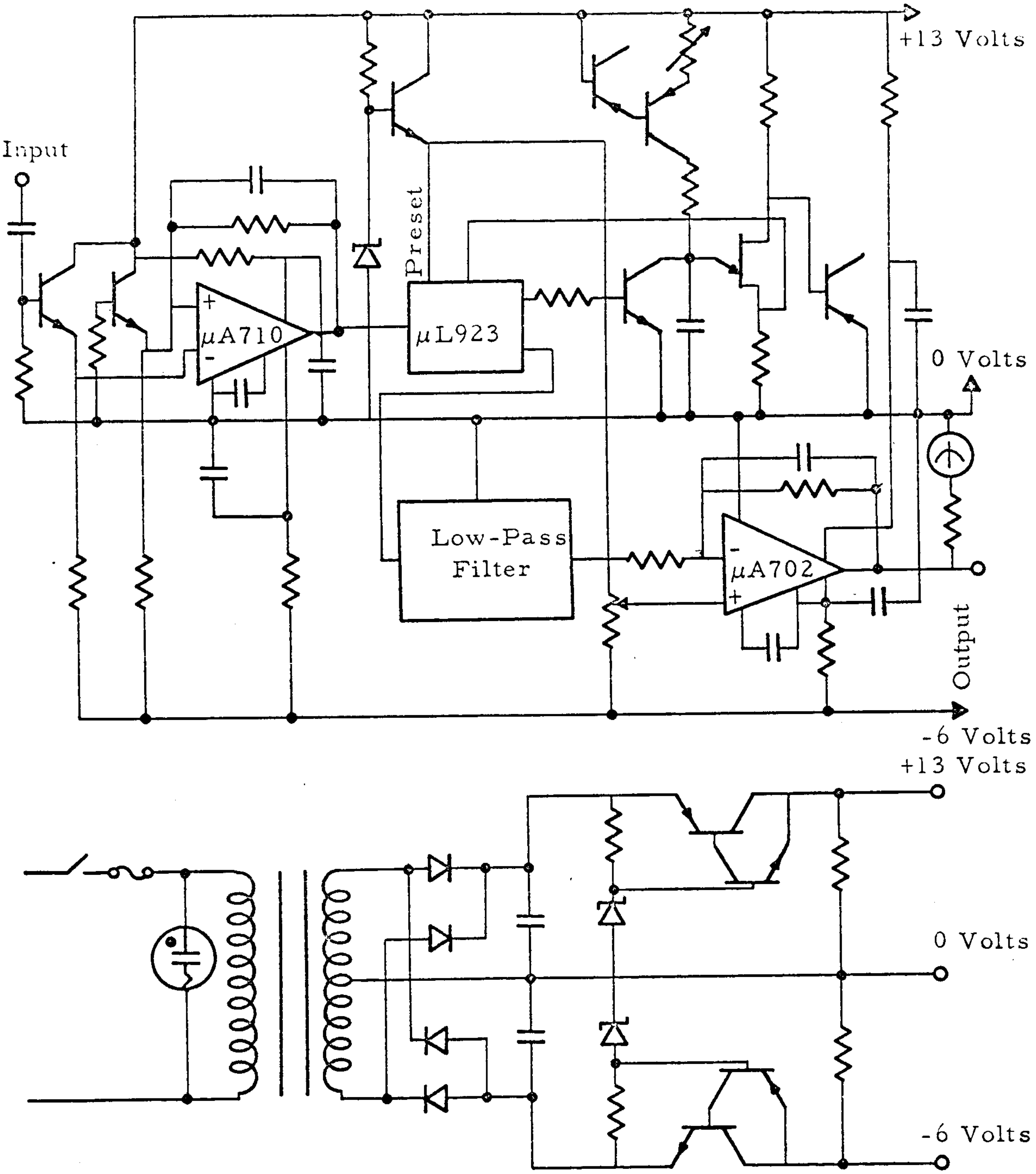


Figure 8. Demodulator for subcarrier of FM-FM strain gage system.

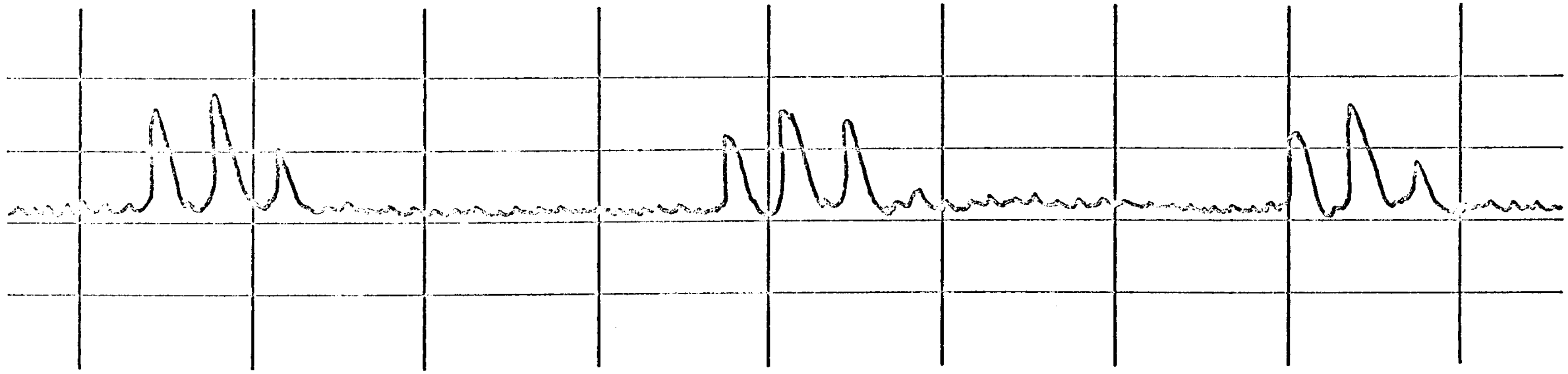


Figure 9. Contractile-Force activity of the stomach of a dog, telemetered by FM-FM, strain gage, telemetry system. This record made 9 March, 1967; transmitter was implanted 23 February, 1967.