Clear and Advance pulses driving a register of experimentally molded elements having the dimensions indicated in Fig. 19 and made with material having a long-pulse threshold of 0.7 oersted. Single-turn coupling-loop circuits with the same effective bias operate equally well.

The detailed analysis of these circuits is difficult not only because of the usual difficulties of dealing with the dynamic properties of highly nonlinear elements, but also because of the relatively complex geometries involved. It is clear that a good deal of the design of these circuits is necessarily based on intuition and empirical results. The circuits described here can be made to operate quite well, however, and the lack of analytical tools is felt more in trying to decide how or when a particular arrangement is optimum. It is hoped that future efforts will result in the development of satisfactory switching models that will make the circuit design procedure routine.

The techniques presented here provide the potential for developing extremely reliable digital circuitry at least for the intermediate computer speed ranges of 0.1 mc to 1 mc clock (or bit) rates.

IX. Acknowledgment

The authors wish to acknowledge the very helpful suggestions and contributions of their colleague, Dr. Douglas Engelbart, to the material presented here.

A Twistor Matrix Memory for Semipermanent Information*

DUNCAN H. LOONEY†

Introduction

A NEW magnetic matrix memory has been developed for the storage of semipermanent digital information. The memory is designed for computers which require random access to stored information that is changed very infrequently. The information is stored in a pattern of permanent magnets arranged on a plastic board. The presence or absence of a permanent magnet is sensed nondestructively by a wire wrapped with a magnetic tape placed close to the permanent magnet. A stored word is read by a linear selection system using a biased core access switch.[1]

The memory is fabricated in modules. A typical module is shown in Fig. 1. The photograph shows a 512-word memory consisting of 32×16 word locations. Each word location stores 26 bits of information. Any word location in the memory may be selected at random and the information read in a period of a few microseconds. The temperature range of operation of the memory is extremely wide.

The concept of storing information in an array of permanent magnets was advanced by the late S. Shackell. Mr. Shackell's work was interrupted by his untimely death and has not been previously reported in the literature. With the development of the twistor,[2] John Janik, who was familiar with the Shackell scheme, suggested its use in such a system to reduce the size of the permanent magnets.

The operation of a store using the 512-word memory module is described in a companion paper.[3] The store, which utilizes all solid-state circuitry, is compared to other systems using photographic or magnetic techniques which can be used for the storage of semipermanent information.

Operating Principle

The information is stored in an array of small permanent magnets. The presence of the magnet is sensed by a wire wrapped with magnetic tape placed close to the magnets. A group of 26 wrapped wires are encapsulated in a plastic tape. The encapsulated wires are then enclosed in a set of copper solenoids as illustrated in Fig. 2. A particular solenoid corresponding to a stored word may be selected by activating one core of the biased core access switch. The bar magnets are arranged in a pattern on the surface of a thin plastic card. Each magnet is located at the intersection of a wrapped wire or twistor and a solenoid. The purpose of the permanent magnet is to inhibit locally the drive field of

* The work reported in this paper was done for the U. S. Dept. of Defense under Contract DA-30-069-ORD-1955.

† Bell Telephone Labs., Murray Hill, N. J.

[1] J. A. Rajchman, "A myriabit magnetic core matrix memory," Proc. IRE, vol. 41, pp. 1407–1421; October, 1953.

[2] A. H. Bobeck, "A new storage element suitable for large sized memory arrays—the twistor," *Bell Sys. Tech. J.*, vol. 36, pp. 1319–1340; November, 1957.

[3] J. J. DeBuske, J. Janik, and B. H. Simons, "A card changeable nondestructive readout twistor store," this issue, pp. 41–46.

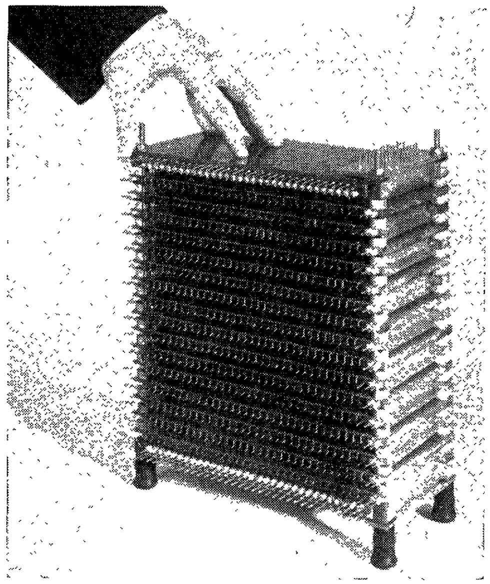


Fig. 1—A 512-word memory module. The unit is composed of 16 frames of 32 words. The cores of the access switch and the multiturn windings are shown. The encapsulated twistor tape threads through the module continuously.

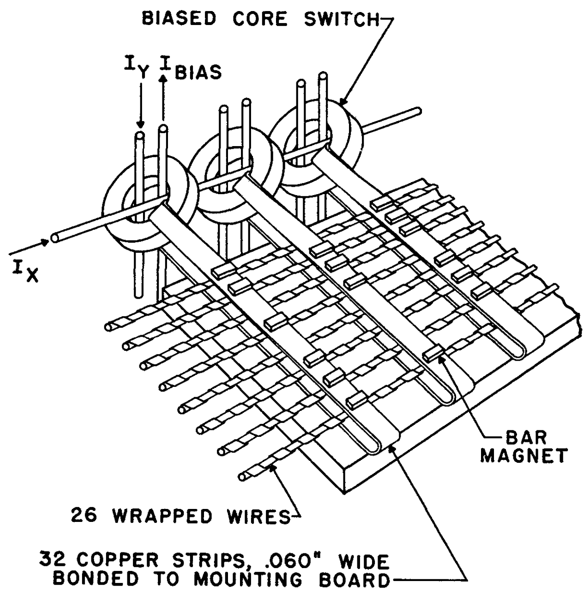


Fig. 2—A section of a memory frame. Three cores of the biased core switch and their word solenoids are shown. The absence of a bar magnet is sensed by the flux reversal of the wrapped wire when a drive current flows in the solenoid.

the solenoid. Thus, the permanent magnet prevents the switching of the wrapped wire located beneath the permanent magnet. The magnitude of the field in the solenoid can be high to achieve fast switching. The field of the bar magnet must, however, be sufficient to inhibit the switching of the wrapped wire. A plane of the module with a complete magnet board is shown in Fig. 3.

In the present design, the solenoids are 1/16 inch wide and spaced 3/16 inch apart. For a current drive of 1.8 amp in the solenoid a switching speed of about 1 μsec

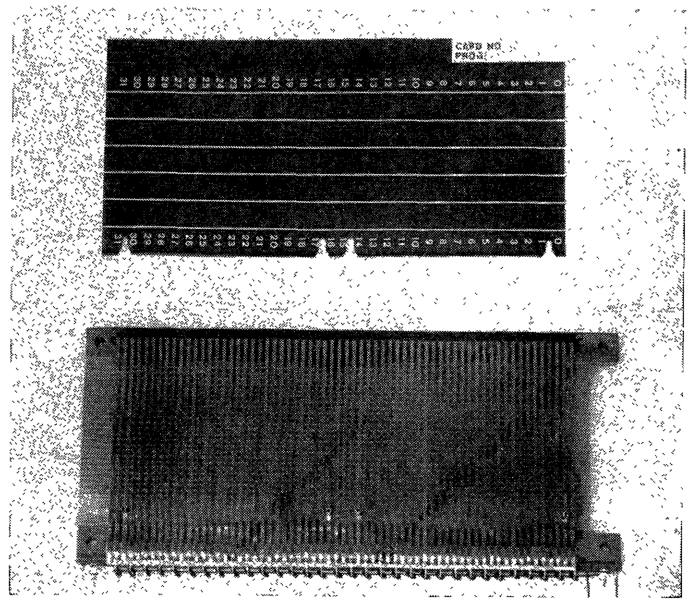
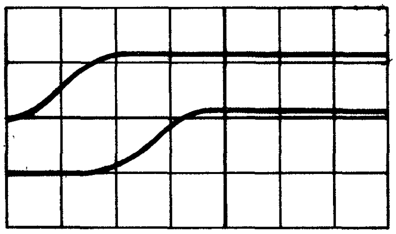


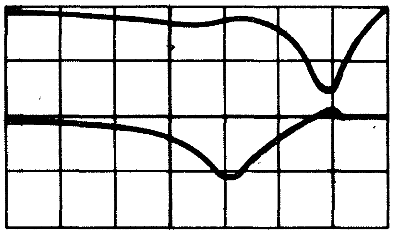
Fig. 3—A memory frame of 32 words and its magnet board. Every other copper strip is used as a solenoid and is attached to an access core. The guide pins of the frame and the corresponding holes of the magnet board are necessary to register the bar magnets at the intersections of the solenoids and the wrapped wires.

is obtained. Current pulses of 600 ma each are applied to four turn X and Y windings of the biased core switch. The bias on each core is 2.4 amp-turns. The X pulse is applied first since the X winding is parallel to twistor wires and results in a larger inductive signal. The sequence of operations is shown in Fig. 4. Time is measured from left to right. The two current pulses are shown in Fig. 4(a). When the applied pulses are removed, the bias current resets the core. The back voltages on the X winding through 32 cores and the Y winding through 16 cores are shown in Fig. 4(b). The core requires about 0.6 amp-turns to generate an output voltage which will drive 1.8 amp through the solenoid. The resultant output signals are shown in Fig. 4(c). Both one and zero output signals are shown by inserting and removing a magnet board. The one signals average 8 mv into 180 Ω while the zero signals are less than 2 mv. The signal-to-noise ratio is 5 to 1. Considering the time necessary to turn on the access switch, a 5-μsec cycle time is easily achieved. Since there are no fundamental limitations on the magnitude of the drive or the amount of flux which must be reversed, shorter cycle periods are possible.

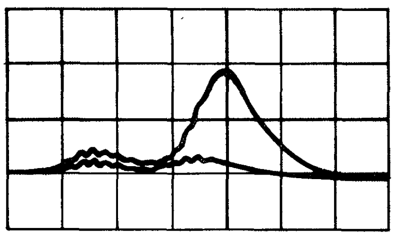
The general performance of the module is shown in Fig. 5. The two current pulses into the biased core switch are shown in Fig. 5(a). The one signals observed on one sensing wire from 32 word locations are shown superimposed in Fig. 5(b). The one signals observed on 26 sensing wires at one word location are shown in Fig. 5(c). The open circuit and matched load output signals are shown in Fig. 5(d) for the 512-word module. The resistive load is 22 Ω and is equal to the sensing wire resistance.



(a)



(b)



(c)

Fig. 4—Electrical characteristics of the module. Time is measured from left to right and each division is 0.5 μsec. (a) Drive currents. The upper trace represents the X selection current, the lower trace the Y selection current. Each division is 500 ma. (b) Observed back voltages. The upper trace is the back EMF on the 4-turn winding through the 16 cores of the Y winding, the lower trace that of the 32 cores on the X winding. Each division is 5.0 volts. (c) One and zero output signals observed with the magnet board present and removed. The first low peaks are due to inductive pickup and shuttle. Each major division is 5 mv. The output load is 180 Ω.

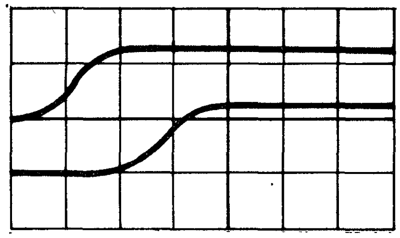
Design of the Permanent Magnet Array

A number of factors must be considered in the design of the permanent magnet array. First, the array of magnets must be simple to manufacture. Since the magnets are the primary storage medium of the memory, they must be capable of retaining their magnetization under very severe conditions. Methods must be devised to register the permanent magnets accurately over the bit locations defined by the wrapped wires and the word solenoids. Finally, the spacing between the individual magnets must be chosen carefully, since one magnet should not disturb either the neighboring magnet or its sensing wire.

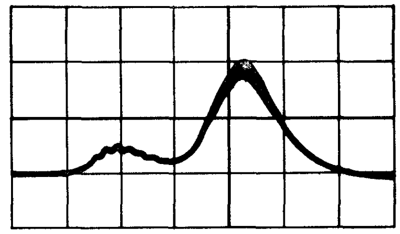
For illustrative purposes, the bar magnet will be considered as two magnetic charges $\pm m$ spaced a distance d apart. The magnetic field H at any distance r perpendicular to the center of the magnet is:

$$H = \frac{md}{[(d/2)^2 + r^2]^{3/2}} \tag{1}$$

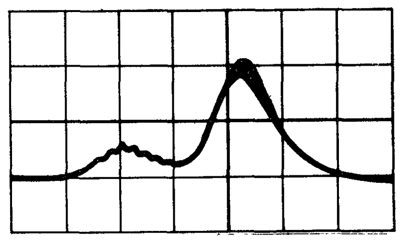
and is directed parallel to the axis of the magnet. There are two limits to be considered. In the limit of $r \to 0$,



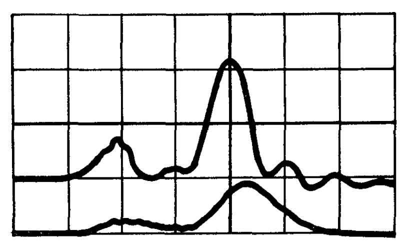
(a)



(b)



(c)



(d)

Fig. 5—Output signals of the module. Time is measured from left to right and each division is 0.5 μsec. (a) Drive currents. The upper trace is the X selection current, the lower trace the Y current. Each major division is 500 ma. (b) 32 "one" signals observed on one sensing wire from 32 cores on one frame. Each major division is 5.0 mv. The load is 180 Ω. (c) 26 "one" signals observed on the 26 sensing wires in one word location. Each major division is 5.0 mv. The output resistance is 180Ω. (d) The output signals for open circuit and matched output loads. The output resistance of the lower trace is 22 Ω and is equal to the resistance of the sense wire. Each major division is 5.0 mv.

(1) reduces to:

$$H_0 = \frac{8m}{d^2} \cdot \tag{2}$$

The field which acts on a sensing wire placed near the magnet is, then, inversely proportional to the square of the length of the magnet. For values of $r \to \infty$, (1) reduces to:

$$H_\infty = \frac{md}{r^3} \cdot \tag{3}$$

Thus, for neighboring positions, the magnetic field is proportional to the length of the magnet.

Ideally, a permanent magnet should have a large effect on the sensing element just underneath it and no effect on any of the adjacent elements. The ratio of the field for r small to the field for r large should be very high. Using the two previous approximations, the ratio is:

$$\frac{H_0}{H_\infty} = \frac{8r^3}{d^3}. \quad (4)$$

In order to reduce the interaction, the magnets should be made as small as possible. A number of other factors, however, prevent the magnet from being made extremely small. The first is that the length of wrapped wire underneath the bar magnet must be large enough to produce a detectable output signal. In addition, the demagnetizing factors associated both with the wrapped wire and with the permanent magnet must be considered. The demagnetizing field of the permanent magnet is inversely proportional to the square of the length d of the magnet. If d is reduced until the demagnetizing field is greater than the coercive force, the effective pole strength m will be reduced. In the case of the wire used as a sensing element, the demagnetizing field of the flux reversed must be less than the applied driving field.

Boards containing the permanent magnet arrays are prepared by etching sheets of Vicalloy I which have been bonded to plastic boards. Vicalloy tape can be obtained in strips about 4 inches wide and 2 mils thick. The Vicalloy is heat treated to produce a saturation magnetization of 5000 gauss and a coercive field of 200 oersteds. The individual magnets are etched using the standard photo resist etched wire technique. Master negatives are prepared such that the individual magnets may be removed by masking out their positions on the negative. Consequently, all information patterns may be prepared from one master negative. The flat form of the magnet simplifies its positioning over the bit location. The bar magnet used is $20 \times 60 \times 2$ mils. The direction of magnetization is parallel to the long dimension. The card containing the magnets is placed in registration by guide pins and is pressed firmly against the solenoids by springs. Consequently, the separation of the permanent magnet from the sensing wire is only a few mils. The two-pole approximation cannot be used to determine the true magnetic field for distances comparable to the bar magnet length. Experimentally, the magnetic field on the wire beneath the permanent magnet is about 20 oersteds. The field on the nearest neighbor is about 1 oersted.

The magnets were spaced unequally in the three dimensions of the present design. In order to reduce the inductance of the solenoid strip encompassing the sensing wires, the wires are spaced 100 mils apart which was considered the minimum distance to avoid lateral interactions. To prevent the permanent magnets of one word from acting too strongly upon the sensing wires in the next word, the individual solenoids are separated 3/16 inch. This distance should be kept small to minimize the length of line over which the output signal must travel before reaching the detecting amplifier. Finally, the individual frames are spaced about ½ inch center to center. One quarter of an inch of this spacing is used for the solenoids, the sensing wires, and the supporting board. The remaining ¼ inch is taken up by the permanent magnet card and its spring assembly. Thus it is quite easy to slip the card in and out as is shown in Fig. 6.

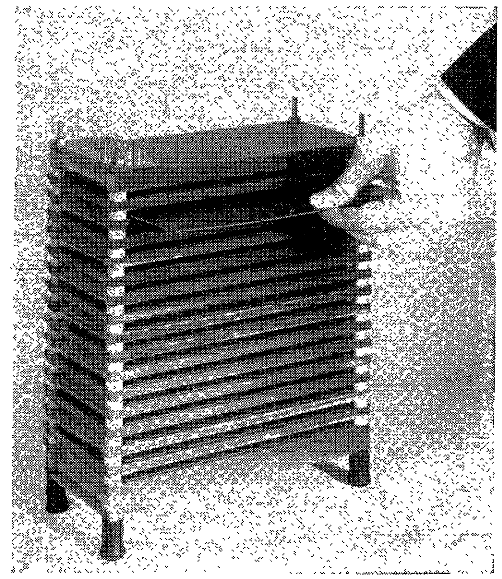


Fig. 6—Rear view of the 512-word memory module. The magnet board is being inserted. It is held against the memory frame by a spring.

The Wrapped Wire Used for Sensing

The twistor wire is shown in Fig. 7. A three-mil copper wire has a magnetic tape wrapped around it at an angle of about 45°. The particular material used is 4–79 permalloy. The tape has a coercive force of about 3 oersteds and a cross section of 5×0.3 mils. The length of the wire per bit is determined by the width of the solenoid employed and is made the same width as the bar magnet for simplicity, *i.e.*, 60 mils.

The cross section of the tape must be adjusted to satisfy a number of conditions. First, the ratio of the bit length to tape thickness determines the demagnetizing field. It is desirable to keep the demagnetizing field small since it decreases the effective driving field. Also, the thickness of the tape should be kept below ½ mil to insure that the eddy current losses are not excessive. The amount of material determines the size of the access core and no more material should be included than is necessary to provide a detectable signal. Finally, the wrapped wire consists of a copper conductor used for the transmission of information wrapped with a magnetic tape used for the detection of information at particular locations. Since the magnetic material acts as a loading on the transmission line, it is desirable to keep the amount of magnetic material to a minimum. The sense wire is a small copper wire and has an appreciable resistance per unit length. It is desirable to use a large diameter wire to minimize the attenuation. Unfortunately, the output signal is determined by the number of times per bit length that the flattened tape wraps around the center conductor. For a given wrapping pitch and bit length, the number of wraps decreases as the diameter increases. Thus, the output signal would be reduced. A compromise must be made between the attenuation which produces a variation of output signal from near bit locations to far bit locations, and the amplitude of the output signals.

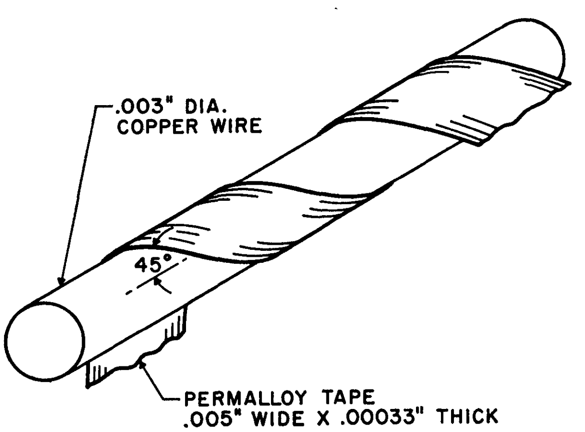


Fig. 7—Helical magnetization by wrapping. The permalloy tape is wrapped continuously around the 3-mil copper conductor.

The uniformity of the output signals is improved if the wire is magnetized in one direction. Consequently the wrapped wire is magnetized before the memory is placed in operation by the passage of a dc current down the wire. The permanent magnet field is directed to maintain the continuous magnetization of the wire. The drive field must switch the wrapped wire into an opposite state of magnetization. As a result, a demagnetizing field is created which opposes the drive field. When the core switch resets the bit, the demagnetization field is in the direction to aid the resetting of the bit. Thus, the wire will remain in a uniformly magnetized state.

The Biased Core Switch

An equivalent circuit for the biased core switch with a constant current input is shown in Fig. 8. The net current drive is the number of ampere turns of the bias since each of the X and Y currents provide the same number of ampere turns as the bias. The core can be represented by two circuit elements. The first is a current sink of NI_0 which represents the fact that a given number ampere turns must be applied to the core before it begins to switch. The core, during the switching operation, acts as a resistance R_c,[4] which is proportional to the total flux of the core divided by the product of the switching coefficient[5] of the material in the core and the mean path length around the core. The core, in switching, generates a voltage which forces current into the load Z_L, which represents the solenoid and its sensing wires. In order to switch current effectively through the core, it is desirable that R_c be made large compared to Z_L. One possibility is to make the flux in the core large.

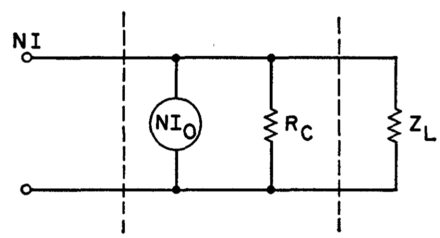


Fig. 8—An equivalent circuit for a biased core switch for a constant current input I. N is the ratio of input to output turns. The switch core is represented by the current sink NI_0 and the resistance R_c.

However, the total back voltage on a selection line is a function of the total inductance of the cores on the line. To reduce the inductance and hence the back voltage, it is desirable to keep the core cross section and thus the total flux small. The minimum flux must be sufficient to supply an output voltage to drive the required current into the load Z_L long enough to complete the sensing. The resistance of the solenoid, its inductance, and the flux, which must be switched in each of the wrapped wire elements contained in the solenoid, determine the required flux of the access core. Since the flux is equal to $\int_0^t v_0 dt$, a convenient nux unit is mv μsec. The flux required by the 26 wrapped wires is about 30 mv μsec. The flux which must be supplied to drive the inductance with a current of 2 amp is about 50 mv μsec while the flux necessary to drive the current through the resistance of the solenoid for 1 μsec is 100 mv μsec. A total of 180 mv μsec of flux must be supplied as a minimum by the access core. The cross section of the core is made sufficiently large to contain 300 mv μsec of available flux. Only about 200 mv μsec of the available flux is used.

The access core is made of ferrite containing cadmium as well as manganese and magnesium. The core has an extremely flat hysteresis loop, $Br/B_s \simeq 0.93$, and a very low coercive field, $H_c \simeq 0.15$ oersted. If a permalloy core were used, only a few wraps would be required to supply the 300 mv μsec of flux. Tape cores with a small number of wraps of $\frac{1}{4}$ or $\frac{1}{8}$ mil tape are not as square as the ferrite core. The tape core has higher dynamic resistance for a given flux than the ferrite core, but this factor is less important than the superior squareness and the lower cost of the ferrite core. In fact, the dynamic resistance of the ferrite core is so large that the current

[4] E. A. Sands, "Behavior of rectangular hysteresis loop magnetic materials under current pulse conditions," Proc. IRE, vol. 40, pp. 1246–1250; October, 1952.

[5] N. Menyuk and J. B. Goodenough, "Magnetic materials for digital computer components," *J. Appl. Phys.*, vol. 26, pp. 8–18; January, 1955.

regulation of the switch is extremely good. The biased core switch improves the rise time of the current delivered to the load compared to the rise time of the drive currents.

Summary

A 512-word 26 bits per word module of a magnetic matrix memory has been developed for the storage of semipermanent information. The memory is capable of random addressing at high cycling speeds. The information is stored in an array of permanent magnets. The presence of a permanent magnet is sensed by a wire wrapped with magnetic tape placed adjacent to the permanent magnet. The magnetic materials used in the memory are permalloy tape, Vicalloy tape, and ferrite cores. As used all materials are relatively insensitive to any change in the ambient temperature and, consequently, the memory may be operated over a wide temperature range.

The electrical characteristics of the memory module can be compared to those of a ferrite core memory. By the use of four turns on the access core, the drive current into the magnetic switch becomes 600 ma. The back voltage, however, is low. The output signal at the word location is 8 mv. The transmission properties of the sense wire must be considered for large memories. The propagation time per bit is about 0.06 mμsec/bit. Since the sense wire is resistive, the output signal may be attenuated as much as 1 db per 512-word module. Larger memories may be made by interconnecting several modules, but the number of modules which may be connected to one sense amplifier is limited by the attenuation of the wrapped wire.

The present memory is an initial model which has been developed to demonstrate feasibility of the system as well as to meet certain operational requirements. Models will be made soon which have improved characteristics. In particular, the size of the memory may be reduced by a factor of two or more. The output signal from the sensed bit may be increased. The transmission line properties of the structure may be improved by making the conducting wire larger.

Acknowledgment

The semipermanent memory is the result of the effort of several people and the author is acting as the reporter for the group. J. Janik suggested the use of the permanent magnet and wrapped wire scheme. Dr. H. L. Stadler contributed the magnetic design, while A. J. Munn has been responsible for the mechanical design of the memory module. Test apparatus design and operation have been contributed by J. A. Ruff and J. L. Smith. The design of the permanent memory has been carried out in parallel with the development of a variable memory under the supervision of A. H. Bobeck. The permanent memory has benefited from the early design and the suggestions of this group. The present project was under the supervision of Dr. F. B. Humphrey. The author gratefully acknowledges his assistance in the preparation of the present paper.

A Card Changeable Nondestructive Readout Twistor Store*

J. J. DeBUSKE†, J. JANIK, Jr.†, and B. H. SIMONS†

Introduction

WITH the steady increase in the required speed and complexity of computing and data processing equipment necessary to handle today's problems, the role of the associated storage systems has been expanding. Generally, a rather large amount of permanent or semipermanent storage capacity is required to store information such as programs, constants, and tables. Besides having a large bit capacity at low bit cost, such stores must be fast, reliable, and flexible in addressing. The twistor sensing an array of small permanent magnets meets these requirements admirably.

The "Twistor" as a memory element was conceived by Bobeck.[1] It may be used as either a memory or a sensing device. It is as a sensing device that it is used in the store described in this paper. The details of the magnetic structure are given in a companion paper.[2]

This memory matrix utilizes cards containing a space for a small magnet at each bit position. A magnet is

* The work reported in this paper was done for the U. S. Department of Defense under Contract DA-30-069-ORD-1955.

† Bell Telephone Labs., Inc., Whippany, N.J.

[1] A. H. Bobeck, "A new storage element suitable for large-sized memory arrays—the Twistor," *Bell Sys. Tech. J.*, vol 36, pp. 1319–1340; November, 1957.

[2] D. H. Looney, "A twistor matrix memory for semipermanent information," this issue, p. 36.