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A Radio-Frequency Nondestructive Readout For Magnetic-Core Memories*

BERNARD WIDROW†

Summary—**It is possible to read information nondestructively from two- and three-dimensional magnetic-core digital computer memories in several microseconds by exciting selected cores with rf currents. If two co-ordinate lines of a core in a memory array plane are driven at slightly different frequencies, a beat-frequency signal is generated whose phase may take on one of two values which are separated by 180 electrical degrees. These two possible phases correspond to the 0 and 1 information states of the core. The beat-frequency signal, separated from the inevitable noises by tuned linear filters, may be phase detected to yield the desired information.**

Introduction

THE SMALL ferromagnetic toroid has proven to be very effective as the basic cell in three-dimensional coincident-current memory systems for digital computers.[1,2] Its success is due to the rectangularity of its hysteresis loop, which gives it the sharp-breaking nonlinearity necessary for multico-ordinate selection and information storage.

The multico-ordinate selection scheme in general use involves destructive reading; that is, the information is destroyed when it is read out.[3,4] Additional time is therefore needed to rewrite the information thus destroyed. A high-speed, nondestructive method of reading is under development which employs radio frequency (rf) currents. Although other applications for rf readout are suggested below, the main concern of this paper is with the coincident-current memory for which this nondestructive readout is inherently suited.

Mechanics of Selection

A necessary characteristic of all linear multico-ordinate selection systems is that the individual cells to be selected must themselves be nonlinear. The excitation applied to the selected cell is a linear combination of the excitations applied to all the selecting co-ordinates, and its magnitude must be greater than the magnitude of the excitations applied to the most heavily driven nonselected cells. The effects possible at the selected cell must be very much greater (in an ideal system, infinitely greater) than the effects possible at any nonselected cell. If the cells themselves are linear, the effects at the selected cell are greater (rather than infinitely greater or very much greater) than those at any nonselected cell.

These ideas are basic to the operation of the coincident-current memory; moreover, the proposed rf readout which makes use of rf current pulses rather than dc current pulses may be evaluated in light of the above criteria.

The Coincident-Current Memory

A magnetic core has the ability to "remember" a single binary number because it may be "permanently" magnetized in either of two directions. 0 may be associated with one remanent-flux state, 1 with the other. Since this single core is to be used as a memory unit, it must be possible to write into it (magnetize it in either direction) and to read out the stored information (sense the remanent-flux direction) when desired. A practical memory would contain many such cores arranged in two- or three-dimensional arrays; the coinci-

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† Staff member, Lincoln Lab., M.I.T., Cambridge, Mass.
[1] J. W. Forrester, "Digital information storage in three dimensions using magnetic cores," *Jour. Appl. Phys.*, vol. 22, pp. 44–48; January, 1951.
[2] W. N. Papian, "A coincident-current magnetic memory cell for the storage of digital information," PROC. I.R.E., vol. 40, pp. 475–478; April, 1952.
[3] J. A. Rajchman, "A myriabit magnetic-core matrix memory," PROC. I.R.E., vol. 41, pp. 1407–1421; October, 1953.
[4] W. N. Papian, "The MIT magnetic-core memory," *IRE Proc. East. Joint Computer Conf.*, pp. 37–42; December, 1953.

dent-current scheme allows individual cores to be selected so that they may be written into and read out of.

Consider the two-dimensional array of cores shown in Fig. 1. Let each core have the dc hysteresis loop shown in Fig. 2. If the drivers are able to supply X and Y currents of magnitude $I_m/2$, any core in the array can be set in the 0 or 1 state by coincidentally exciting the corresponding X and Y lines (single-turn exciting windings) with currents of the proper polarity for a time long enough to permit flux switching. Only the selected core receives the full I_m; the half-selected cores receive $I_m/2$ which is of too small a magnitude to cause flux switching and therefore may disturb but will not destroy the stored information.

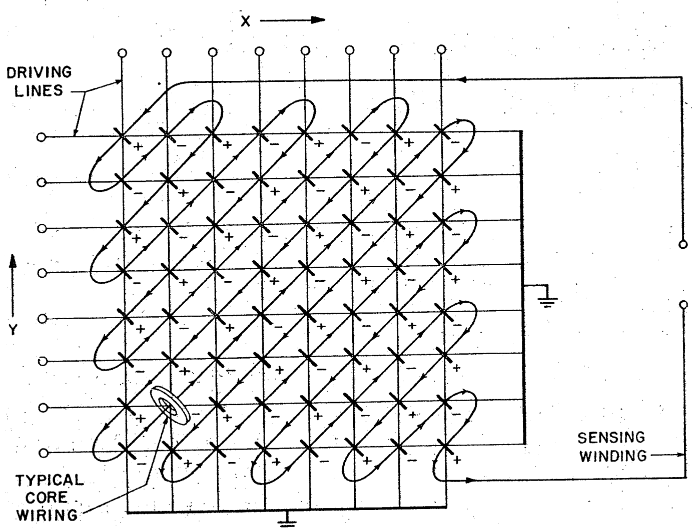

Fig. 1—8×8 model of a memory array plane.

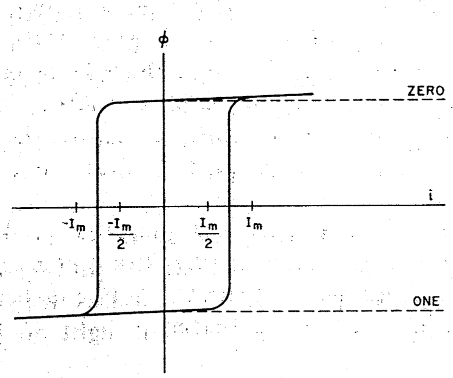

Fig. 2—D-C hysteresis loop of a typical magnetic core.

The use of coincident currents for reading is similar to their use for writing. In order to sense the contents of a core in a memory plane, 0 is written into it. If the selected core already contains a 0, the 0 state remains, and only very small flux changes take place. If, on the other hand, the selected core contains a 1, full flux reversal will occur. A sensing winding (see Fig. 1) threaded through every core in the array will exhibit either a small noise pulse corresponding to a 0 in the selected core or a much larger and longer voltage pulse signifying that the selected core had contained a 1. This pulse readout is destructive, and provision must be made (and time allowed) for rewriting if the information is to be retained.

The signal induced in a sensing winding during readout is not generated by the selected core alone. In a 4×4 planar array of cores, there are always six half-selected cores producing noise when a selected core is pulsed. The sensing winding passes through adjacent cores on a common X or Y driving line in the alternating fashion shown in Fig. 1. The intention is that half-selected noises should cancel as they would if the half-selected outputs were all identical. They are not identical because of variations in properties among the cores; more significant, however, is the difference in the noise outputs of a core containing a 1 and of the same core storing a 0. The resultant of these noises is proportional to n for an $n \times n$ array, while the signal size is fixed. Signal-to-noise ratios are inversely proportional to n for a given core type.

Nondestructive RF Readout

At the expense of more elaborate driving circuits, an rf readout system is obtainable which could be fast (speed determined mainly by frequencies of rf driving currents; information is read nondestructively, so that time for rewriting need not be spent), and reliable in large systems (signals separated from the inevitable noises by tuned filters).

A Two-Dimensional RF Readout System

If the X and Y lines corresponding to a chosen core in a memory plane (Fig. 1) are driven simultaneously by two sinusoidal rf currents of frequencies ω_1 and ω_2, these currents add at the selected core (a nonlinear device) and cause it to induce a difference-frequency beat in the sensing winding. The frequencies of the two driving currents are made to be much greater than their difference so that the difference-frequency signal may be easily separated from the high-frequency noises.

According to the selection criteria, rf readout gives an ideal type of selection. The only cell in the two-dimensional system able to generate a difference-frequency signal is that one at which the two rf currents are superposed within a nonlinear magnetic circuit. The half-selected cores (those sharing a single X line or a single Y line with the selected core) produce only noises at the fundamental drive frequencies and at their higher-order harmonics. These noises are linearly superposed in the sensing winding and may be removed by linear passive filters.

It is possible to detect the remanent-flux state of the selected core from the phase of the difference-frequency signal; this phase may assume one of two values (separated from each other by 180 degrees) corresponding to a 1 or a 0 stored in the selected core. To show that a difference-frequency signal is so generated and to predict the operation of a core in a memory plane during rf readout, a single core rf pulse tester was constructed (see Fig. 3). (Since a trigger pulse starts both oscillators, the two rf currents and the difference-frequency voltage from the tuned amplifier are locked in on the same sweep.) As predicted, polarity of the difference-frequency signal reversed with the core's remanent flux.

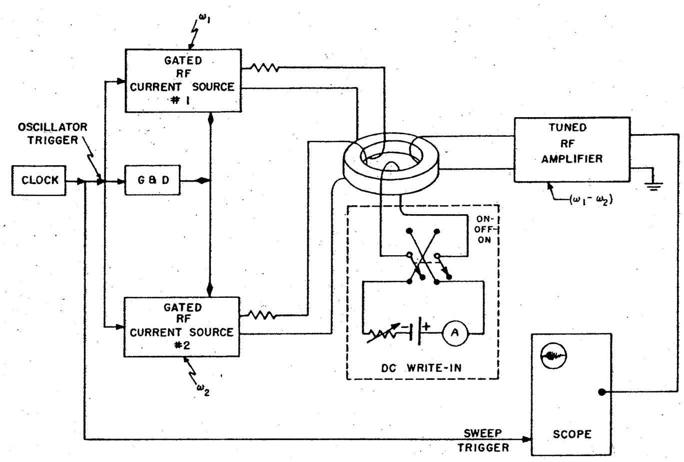

Fig. 3—RF pulse tester.

Analysis of Beat Generation

Assume that the two rf hysteresis loops of the two memory states are the single-valued nonlinear analytic $\phi - i$ relations of Fig. 4, and that the type of symmetry they show to each other is the same as the symmetry between the top (0 state) and bottom (1 state) of the dc hysteresis loop of Fig. 2. The relationship between

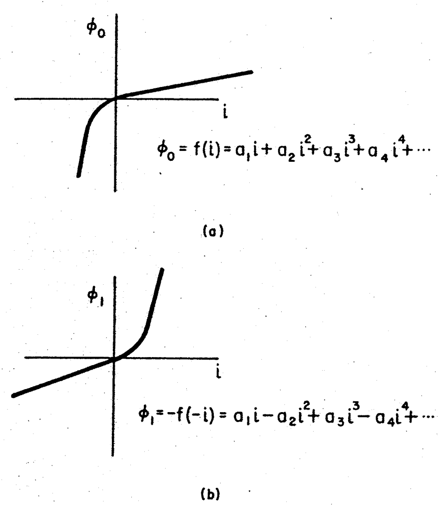

Fig. 4—Incremental flux vs instantaneous current when core stores 1 and 0.

ϕ_0 and ϕ_1 of Fig. 4 becomes apparent when it is observed that either curve may be made identical to the other by a "double flip" which reverses both the flux and current scales. If the 0 state incremental flux $\phi_0 = f(i)$, then the 1 state incremental flux $\phi_1 = -f(-i)$. Let the incremental fluxes be expanded in a Taylor's Series in the instantaneous current i:

$$\phi_0 = f(i) = a_1 i + a_2 i^2 + a_3 i^3 + \cdots \quad (1)$$

$$\phi_1 = -f(-i) = a_1 i - a_2 i^2 + a_3 i^3 - \cdots \quad (2)$$

To generate beats, let the two sinusoidal currents flow simultaneously. Then

$$i = (\sin \omega_1 t + \sin \omega_2 t) \quad (3)$$

$$\phi_0 = a_1(\sin \omega_1 t + \sin \omega_2 t) + a_2(\sin \omega_1 t + \sin \omega_2 t)^2 + \cdots \quad (4)$$

$$\phi_1 = a_1(\sin \omega_1 t + \sin \omega_2 t) - a_2(\sin \omega_1 t + \sin \omega_2 t)^2 + \cdots. \quad (5)$$

The first terms of (4) and (5) cause outputs at the two fundamental driving frequencies. The second terms are of the form

$$a_2(\sin \omega_1 t + \sin \omega_2 t)^2 = a_2(\sin^2 \omega_1 t + \sin^2 \omega_2 t + 2 \sin \omega_1 t \sin \omega_2 t). \quad (6)$$

Outputs at the second-harmonic frequencies of the fundamental driving frequencies are caused by the terms $a_2 \sin^2 \omega_1 t$ and $a_2 \sin^2 \omega_2 t$. The remaining component is:

$$2a_2 \sin \omega_1 t \sin \omega_2 t = a_2 \cos(\omega_1 - \omega_2)t - a_2 \cos(\omega_1 + \omega_2)t. \quad (7)$$

This gives a sum-frequency signal and the desired difference-frequency signal.

The squaring arising from the nonlinear addition of two sinusoids creates the difference-frequency-flux component. Notice that the sign of the coefficient a_2 is reversed as the core is switched. Physically, this means that the curvature of the ϕ-versus-i path is positive or negative, depending on whether the core stores a 1 or a 0. It then follows that the polarity of the difference-frequency signal induced in a sensing winding reverses when the core's information content is changed.

The above shows that core properties are not critical. Different cores may exhibit different values of the coefficient a_2. Although this would cause them to generate beats whose amplitudes may differ, their phases must be discrete. This has been verified experimentally for cores of many sizes and materials. The perfection of the polarity reversal has also been checked to within a few degrees (this check was limited by scope accuracy) for every core tried.

Why RF Readout Is Nondestructive

The periods of the rf waves are very much shorter than the response times of the cores for the current magnitudes involved. The same internal mechanisms that limit the switching speed of a core driven by dc pulses are believed to prevent the destruction of information by rf currents even when the zero-to-peak of the rf excitation is made many times greater than the coercive force. If any flux switching is done during a half cycle, it is immediately undone during the next half cycle. If a small dc bias is applied, such that the bias plus the zero-to-peak of the rf excitation exceeds the coercive force, then the core will slowly switch in the direction of the bias. In the absence of dc bias, a core may be rf driven indefinitely and experience only negligible deterioration of its remanent flux.

Conclusion

An experimental 16×16 memory plane was constructed of steel-ribbon cores having the following specifications: 10 wraps of 4-79 molybdenum Permalloy-ribbon, $\frac{1}{8}$-mil thick, $\frac{1}{8}$-inch wide, wound on a $\frac{1}{8}$-inch bobbin. These cores had been rejected for use in the usual coincident-current memory because of their nonuniformities. They had shown variations of ten to one among some of their pulse readout signals.

It was possible to sense any core in this array plane using the rf readout. X and Y coordinate lines were manually selected by clip-lead connection to two pulsed rf current sources which supplied currents at 5.4 and 6.8 megacycles respectively. (Fig. 5 shows an rf readout system for a 4×4 memory.)

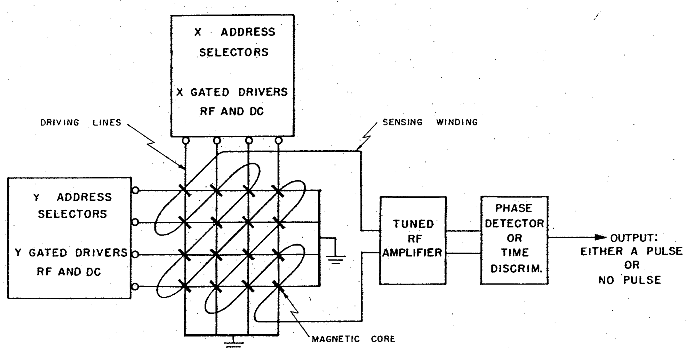

Fig. 5—An rf readout system.

Typical driving-current and sensing-amplifier waveforms are shown in Fig. 6. The frequencies chosen were arbitrary but convenient for the available equipment. The desired information is discernible about 2 microseconds after the beginning of the reading operation: the rf output of the sensing amplifier requires about 15 microseconds to build up. If the rf readout is to be used to read information from random addresses in high-speed succession, transient recovery time must be sharply reduced from that shown in Fig. 6. An obvious solution is reduction of the driving time of the rf current sources from the 15 microseconds of Fig. 6 (for the sake of illustration, made longer than necessary) to about 1 or 2 microseconds. The bandwidth of the sensing amplifier might be increased for faster rf transients. (The amplifier used had a bandwidth of 75 kilocycles.) To achieve the same noise rejection with the tuned sensing amplifier, it would be necessary to raise the driving frequencies. It would also be possible to use an electronic damper in the sensing amplifier that could be gated on as soon as the desired information is obtained.

A practical memory would use its electronic address-selection and current-driver circuits for both the rf readout and the usual pulsed write-in. Although such circuits have not yet been tried, experiments made show that rf readout could be used in large three-dimensional memories. Other applications of rf driven cores seem promising. A magnetic-core may be used as a low impedance mixer in communications circuits by applying two or possibly several inputs to separate primary windings. The mixed output is induced in a secondary winding. Magnetic cores may also be used in carrier-type logical circuits, where advantage may be taken of their ability to detect coincidences (the generation of beat-frequency signal depends upon the presence of two or more inputs), and where the necessary information storage could be accomplished by the cores themselves. The prime advantage of magnetic cores for these mixing applications lies in the *long-term stability* of their nonlinear knee, as contrasted to the short-term stability of vacuum-tube mixers.

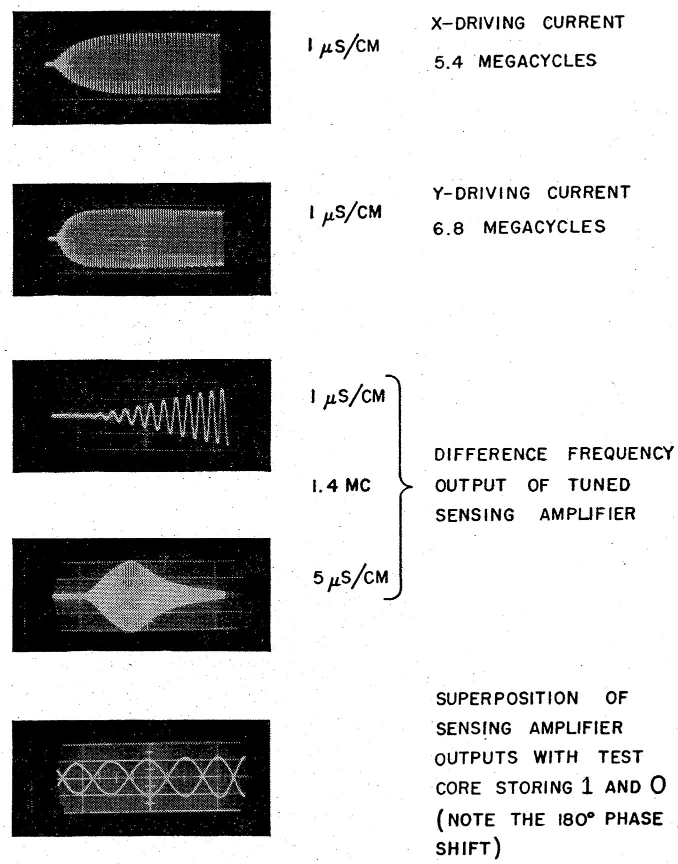

Fig. 6—Typical driving-current and sensing-amplifier wave forms.

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