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The Chain Magnetic Memory Element

Nondestructive reading of orthogonal-field memory elements, in particular metallic tape memory cores in which an interrogating current through the tape material is employed, has been described in the literature,[1,2] and many workers have reported on other orthogonal field memory elements. The experimental element described in this paper differs in geometry from previously proposed orthogonal field memory elements and provides all memory functions.

The new magnetic memory element, named the "chain" (because of the chain-like appearance of word lines of series connected elements) is a planar Permalloy toroid in which the fields required for memory operation are produced by current linking the toroid and current through the body of the toroid. This communication presents experimental results which demonstrate destructive reading, orthogonal coincident current writing, and nondestructive reading. Word lines of series-connected elements permit the construction of word-organized memories in which each element is linked by only one conductor.

Element description

A single chain element is shown in Fig. 1, where S_1 and S_2 are the connections to the planar toroid T for the currents required for destructive reading, orthogonal coincident current writing, and nondestructive reading; W is a conductor which serves as the bit/sense winding or, in one possible mode of operation, as the interrogate winding.

Elements are etched from sheets of annealed Permalloy (79% Ni, 17% Fe, 4% Mo) with the following dimensions: toroid outside diameter, 0.25 inch; inside diameter, 0.15 inch; connection tab width, 0.10 inch; and thickness, 0.0005 inch. The residual flux density, B_R, of Permalloy is $\approx$ 5000 gauss, yielding for the dimensions above a toroidal residual flux, ϕ_R, of $\approx$ 0.8 maxwell. The toroidal dc threshold is $\approx$ 100 milliampere turns.

The experimental element described above is considerably larger than the elements that would be used in any memory application, the experimental size chosen being a compromise providing experimental convenience while avoiding toroidal leakage flux.[3]

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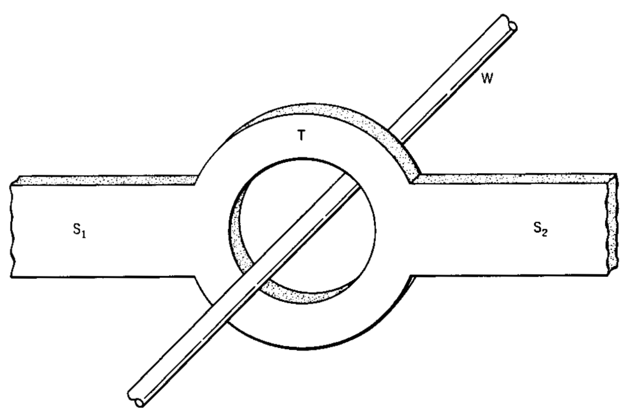
Destructive reading

Destructive reading is performed by passing a sufficiently large current, I_S, through the body of the element. As shown in Fig. 2a, I_S divides equally between the upper and lower branches of the toroid and produces fields on its top and bottom surfaces, and through most of its volume, that are perpendicular to the toroidal direction of initial magnetization, 0 or 1. When I_S is applied, the domains are reoriented parallel to toroid radii, the direction of radial orientation being a function of location (i.e., top surface vs bottom surface and upper branch vs lower branch). Reading thus switches the toroid from either the 0 or the 1 state to X, the cleared state, shown in Fig. 2b, inducing in the conductor linking the toroid a signal whose polarity indicates the initial state of the element. When I_S ends, the toroidal magnetization remains at X with the domains in a stable quasi-random arrangement.

Orthogonal coincident current writing

Figure 3 shows, between the times t_1 and t_2, the currents I_S and I_T used for orthogonal coincident current writing. Assuming that the element is in the X state, as defined above, coincident application of the damped sinusoidal current I_S and the pulse $\pm I_T$ switches the toroid, as a

Figure 1 Chain element



function of the polarity of I_T, to the 0 or 1 state. These states, as indicated in Fig. 2b, are at $\approx 85\%$ of ϕ_R, and disturb sensitivity tests with $>10^6 \pm I_T$ disturb pulses did not reduce the toroidal magnetization below 70% of ϕ_R. Toroidal switching voltages during writing after destructive reading, as observed with a single turn sense winding, are shown in Figs. 4b, 4c, and 4d between the times t_1 and t_2 shown in Fig. 4a.

Destructive reading is combined with coincident current writing by the addition of a half-cycle to I_S prior to time t_1, as indicated in Fig. 3 by R and as shown in Fig. 4a. Assuming that the element is in either the 1 or the 0 state as the result of a previous write cycle, R is sufficiently large to switch the toroid to X, producing the output signals indicative of state shown in Figs. 4b, 4c, and 4d prior to the time t_1.

The mechanism of orthogonal coincident current writing is not completely understood, but some qualitative conclusions can be reached in view of the known reduction of switching thresholds by orthogonal fields. If I_T is applied in the absence of I_S it does not produce toroidal switching since, as mentioned previously, the element is not disturb sensitive. Further, only 85% of the toroidal flux is switched by the coincident application of I_S and I_T, leading to the conclusion that some region of the element does not enter into toroidal switching. With reference to Fig. 5, it is obvious that I_S produces orthogonal internal fields which are zero at the center plane of the toroid and which increase monotonically to oppositely directed maxima at the top and bottom surfaces of the toroid. Since the fields produced by I_S are zero at the center plane and small in the immediately adjacent regions, the central region Z, shown shaded in Fig. 5, is the region that does not enter into toroidal switching. In this region the orthogonal fields produced by I_S are too small to sufficiently reduce the threshold for toroidal switching. Considering next the pairs of regions A through E of Fig. 5, which do switch, it is evident from the waveforms of Fig. 4 that toroidal switching occurs in steps, each step corresponding to a zero crossing of I_S. Since, as mentioned previously, the internal fields produced by I_S increase from zero at the center plane to maxima at the surfaces, regions A through E switch sequentially during the five zero crossings of I_S that occur in a write operation, yielding the stepwise changes in toroidal magnetization indicated in Fig. 2b.

In view of the conclusions above, an improved chain element can be proposed in which the regions Z through D of Fig. 5 would be a conducting nonmagnetic material, the region E remaining as magnetic material. In addition to reducing the resistance of word lines of series connected elements, the proposed element would permit a reduction in the number of cycles in I_S, possibly to the point where more conventional pulse excitation of word lines rather than damped sinusoidal excitation would be feasible.

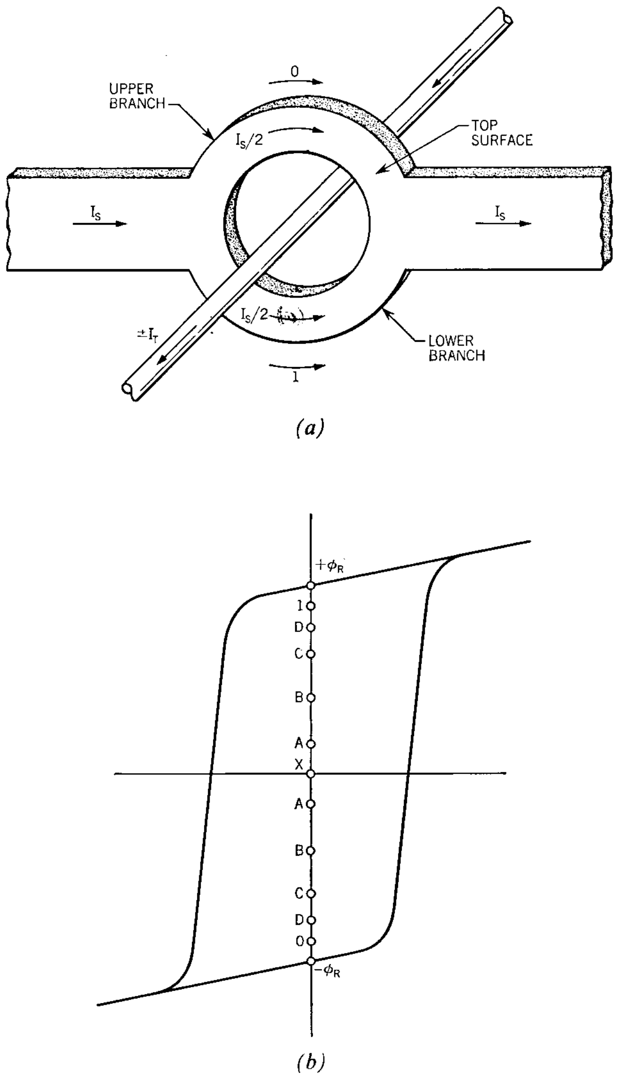
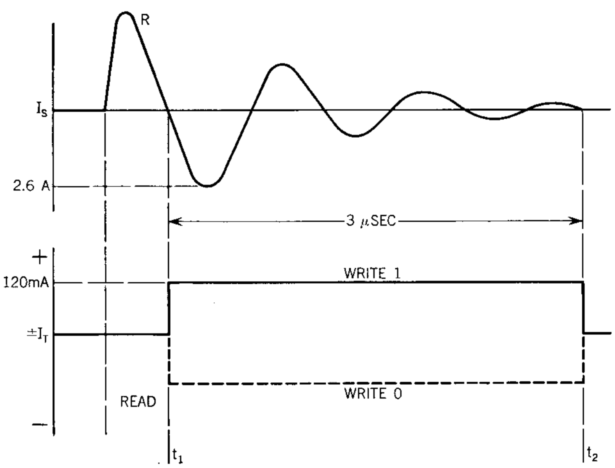


Figure 2 Destructive reading and orthogonal coincident current writing; (a) nomenclature; (b) toroidal flux states.

Figure 3 Idealized waveforms for destructive reading and orthogonal coincident current writing.



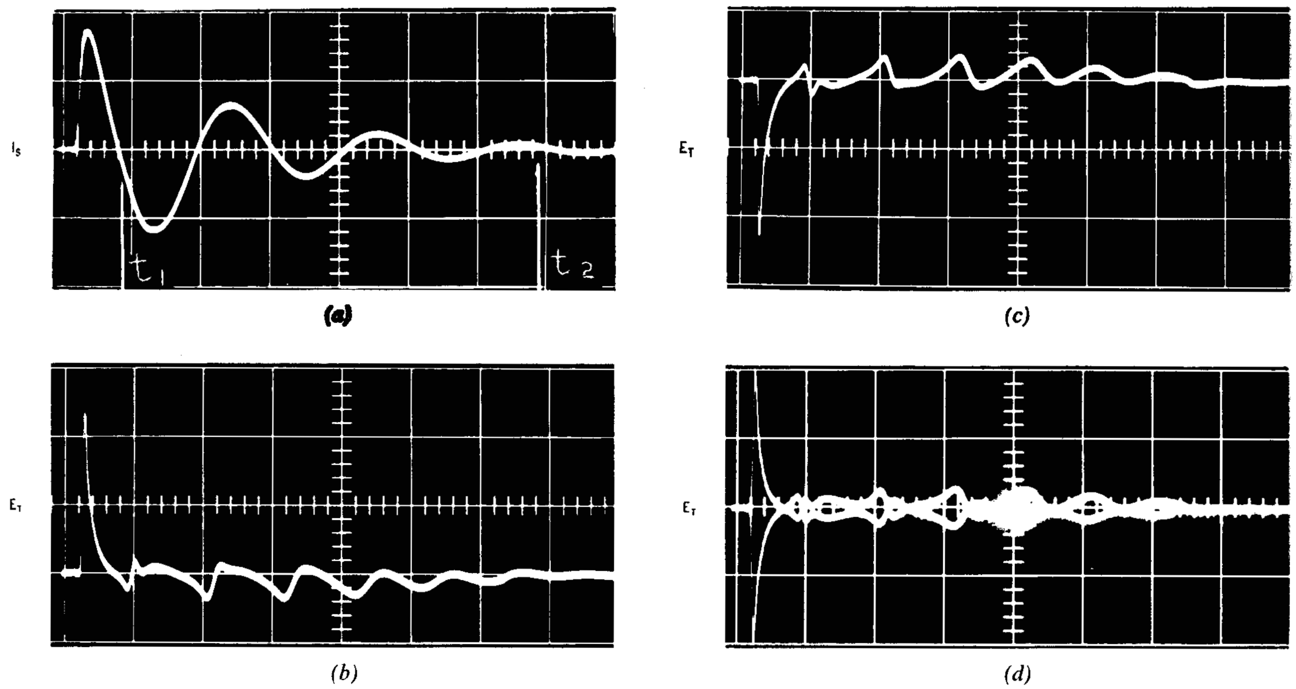


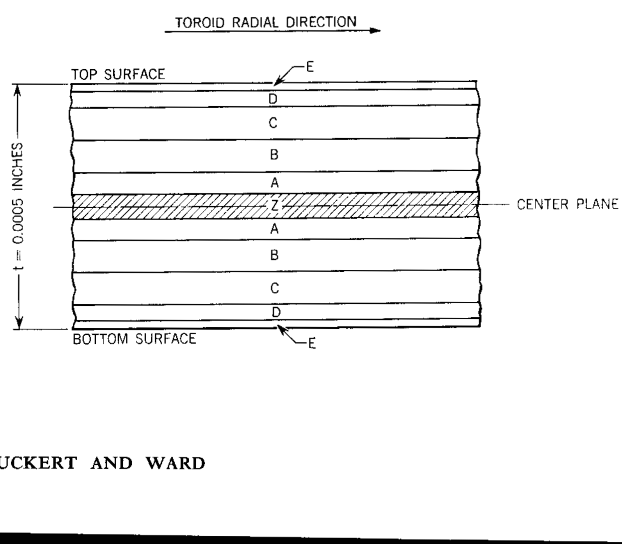
Figure 4 Word current and toroidal switching voltage waveforms for destructive reading and orthogonal coincident current writing (horizontal: 0.5 sec/div.): (a) I_S (vertical: 2 amp./div.); (b) E_T for read 1, write 1 (vertical: 40 mV/div.); (c) E_T for read 0, write 0 (vertical: 40 mV/div.); (d) E_T for read 1, write 0 and read 0, write 1 superimposed (vertical: 40 mV/div.).

Nondestructive reading

Three modes of nondestructive reading (NDR) have been observed in the experimental chain element, and in this section descriptions of operation and experimental results for these modes are presented.

Mode 1 NDR is a modification of destructive reading in which the amplitude and width of the interrogating pulse I_S are reduced to magnitudes where substantially no irreversible switching occurs. Although the internal mechanism of NDR is not completely understood, the following qualitative description can be given. The element shown in Fig. 6a is assumed to be magnetized in the 0 direction and the two small regions X and Y are chosen for detailed consideration. In the enlarged views of X and Y the vectors $\mathbf{m}_t$ and $\mathbf{m}_b$ represent the quiescent toroidal magnetization and $\mathbf{H}_t$ and $\mathbf{H}_b$ represent the internal fields produced by I_S in the top and bottom regions of the element, respectively. I_S transiently reorients the magnetization vectors through the angle α on all four surfaces and thus decreases the toroidal magnetization at each point, $\Delta\mathbf{m}_t$ on the top surface and $\Delta\mathbf{m}_b$ on the bottom surface. Similar reorientations are occurring throughout the majority of the toroid and it is the aggregate of these which induces a voltage in the sense winding linking the toroid. When I_S is removed, internal forces return the toroidal magnetization to its initial state, inducing a voltage of the opposite polarity in the sense winding. A summary of mode 1 NDR is shown in Fig. 6b for the 0 and 1 states and for $+I_S$ and $-I_S$. In this mode the polarity of the NDR output voltage, E_T, is a function of the state of the element regardless of the polarity of I_S. The element has been interrogated nondestructively with pulses of from 4 nanoseconds to 1 microsecond in duration. The tests showed that the amount of flux irreversibly switched during NDR is a function of the amplitude and width of I_S and that, for a given pulse width, the output voltage on the nth interrogation is approximately a linear function of dI_S/dt.

Figure 5 Cross section view of a portion of a chain element (direction of I_S perpendicular to plane of paper).



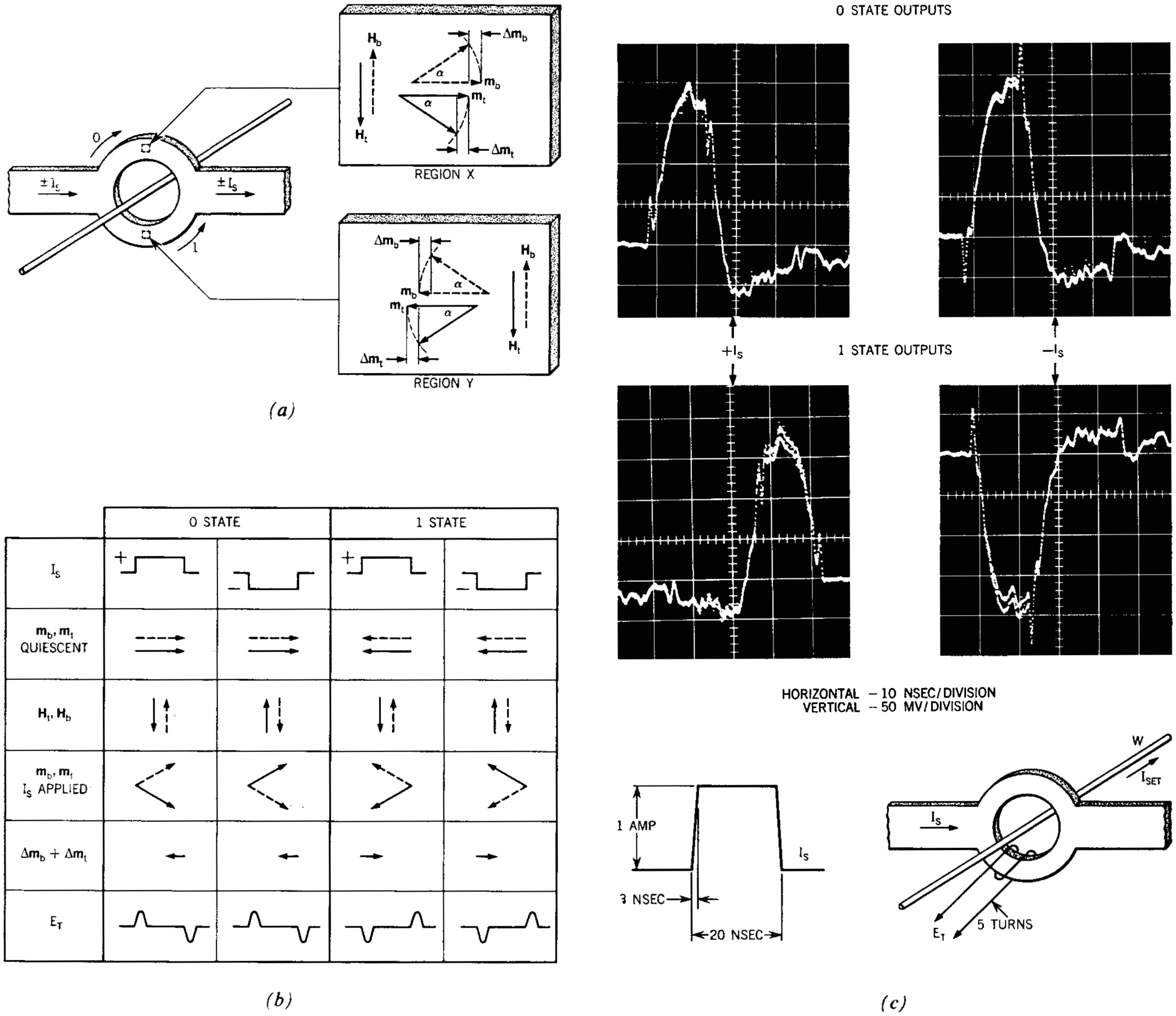


Figure 6 Nondestructive reading (mode 1): (a) nomenclature; (b) tabular summary; (c) waveforms and experimental conditions.

Typical experimental mode 1 test conditions and waveforms are shown in Fig. 6c where the NDR voltages for the first and nth($n > 10^6$) interrogations are superimposed in all four photographs. In this experiment, and in the mode 2 and 3 experiments described below, the element was initially set at $\pm\phi_R$ by a current through W.

For the descriptions of mode 2 and mode 3 NDR the angle $\beta \approx \alpha/2$ is defined where α is as shown in Fig. 6a. In mode 2 a dc bias current, I_B, is applied to the element in addition to the NDR pulse I_S. After the toroid is initially set to either the 0 or 1 state I_B reorients $\mathbf{m}_t$ and $\mathbf{m}_b$ at the angle β to the toroidal orientation. I_S, as a function of its polarity relative to I_B, further reorients $\mathbf{m}_t$ and $\mathbf{m}_b$ and produces either an increase or a decrease in the toroidal components of the magnetization. Thus, the polarity of the NDR voltage E_T in this mode of operation is a function of the polarity of I_B, the polarity of I_S, and the state of the element. Experimental conditions and waveforms are shown in Fig. 7 for magnitudes of I_B and I_S which yield equal positive and negative output signals. The NDR signals for the first and nth ($n > 10^6$) interrogations are superimposed in the four sets of traces shown in Fig. 7.

Mode 3 NDR is the operational inverse of mode 2 NDR since the NDR pulse I_T is applied to a conductor linking the toroid while the element itself is the sense winding. In this mode it is necessary that a bias current I_B, through the element, also be present since operation is dependent on changes in the radial components of $\mathbf{m}_t$ and $\mathbf{m}_b$ which I_B orients at the angle β to the toroidal direction. The interrogating pulse I_T transiently reorients $\mathbf{m}_t$ and $\mathbf{m}_b$, producing either increases or decreases in the

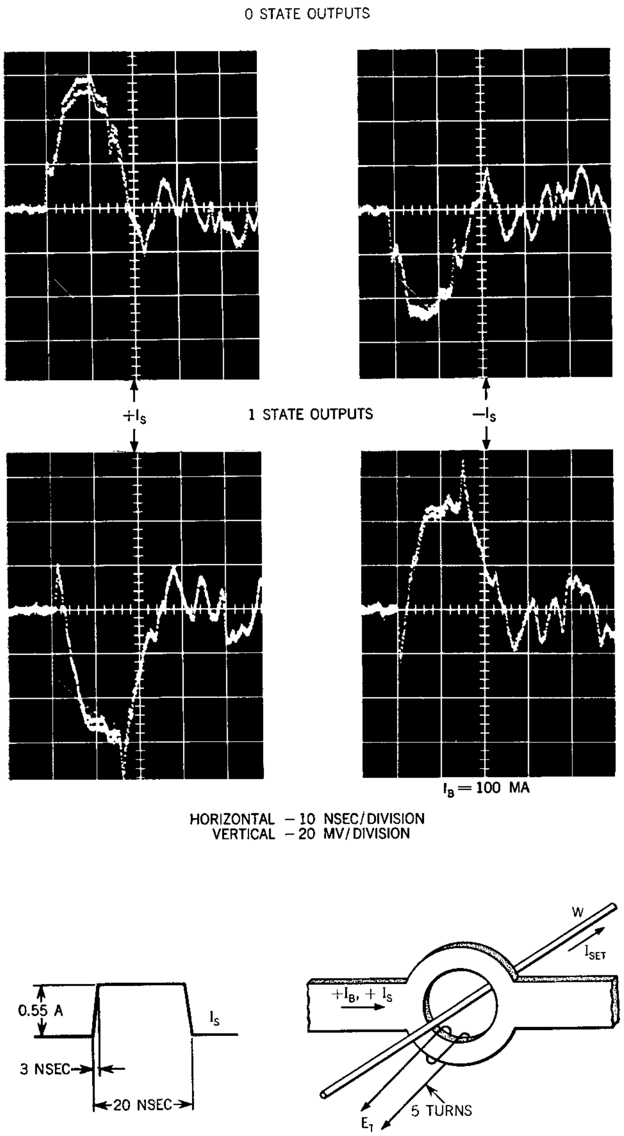


Figure 7 Nondestructive reading (mode 2): waveforms and experimental conditions.

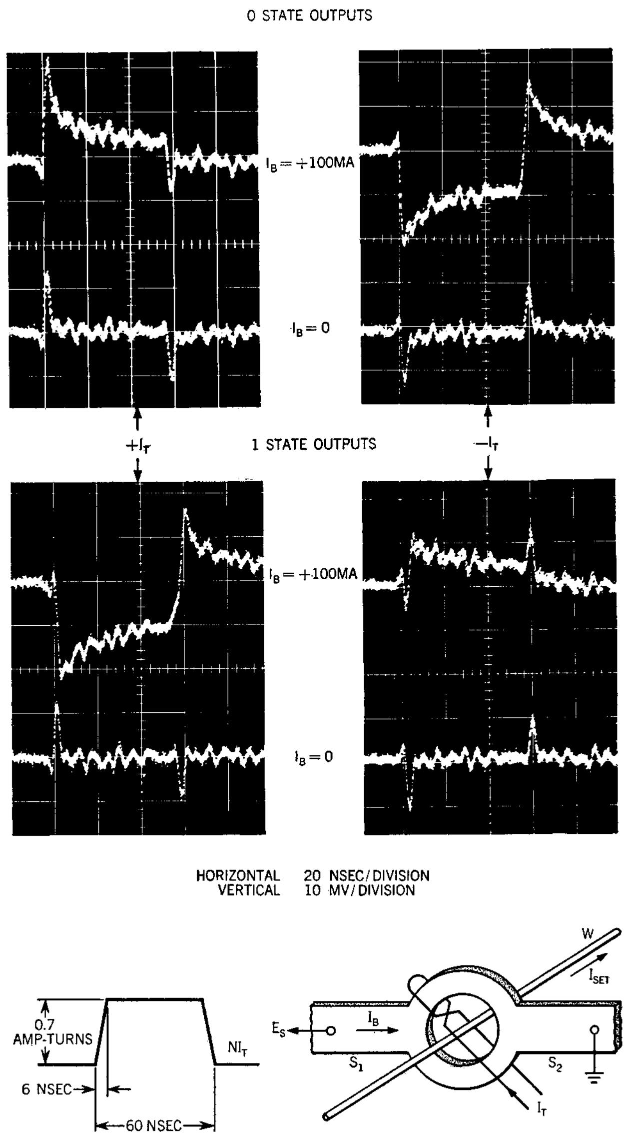


Figure 8 Nondestructive reading (mode 3): waveforms and experimental conditions.

magnitudes of the radial components of flux which link the upper and lower branches of the toroid, inducing a voltage across the element which appears across the tabs S_1 and S_2. The polarity of the NDR output voltage, E_S, in this mode of operation is a function of the polarity of I_B, the polarity of I_T, and the state of the element. Experimental conditions and waveforms are shown in Fig. 8. In the upper trace of each photograph the NDR voltages for the first and nth ($n > 10^6$) interrogations are shown superimposed for $+I_B$; in the lower traces the outputs for $I_B = 0$ are shown, demonstrating that in this mode of NDR I_B must be present.

Conclusions

The versatility, relatively high speed, and simplicity of the chain element make is applicable to a number of word-organized memory systems, existing and proposed. This is particularly true if practical elements with conducting nonmagnetic inner regions are developed. Consider, for example, the word organized destructive read memory with common bit/sense lines. In this application the chain element has a number of advantages, both electrical and mechanical. Since substantially all of the flux switched by word line currents is useful flux (useful, in the sense that it contributes to the generation of sense line signals), word line driver requirements are eased because of low back voltages. Further, the planar geometry of series connected elements permits the construction of word lines as low impedance transmission lines by associating a ground plane (perforated to permit insertion of the bit/sense lines) with each word line. The thinness of the element, even with an associated ground plane, permits array construction with high densities of elements per unit length of the bit/sense lines in which the entire array wiring process consists of the insertion of a single straight bit/sense wire at each bit position. Since the chain element provides substantially complete flux closure, the element is relatively insensitive to influence by external fields. Reductions in the planar dimensions of chain elements can be projected which will yield word line lengths comparable to those now found in memories and significant reduction in the required word and bit drive currents.

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