DESIGN, DEVELOP AND FABRICATE A FEASIBILITY MODEL OF A FERRIMAGNETIC MEMORY USING AN OPTICAL ACCESSION SYSTEM FOR READ WRITE FUNCTIONS

NAS8-20509

Final Report

November 22, 1966

prepared for

National Aeronautical and Space Administration

Att: NAS8-20509

George C. Marshall Space Flight Center

Huntsville, Alabama

prepared by

Univac Division of Sperry Rand Corporation,
Blue Bell, Pa., Norman Goldberg, author

N67-23266
(ACCESSION NUMBER) 115 (PAGES) CR 83539 (NASA CR OR TMX OR AD NUMBER)
(THRU) 1 (CODE) 08 (CATEGORY)
FACILITY FORM 602

DESIGN, DEVELOP AND FABRICATE A FEASIBILITY MODEL OF A FERRIMAGNETIC MEMORY USING AN OPTICAL ACCESSION SYSTEM FOR READ WRITE FUNCTIONS

NAS8-20509

Final Report

November 22, 1966

prepared for

National Aeronautical and Space Administration

Att: NAS8-20509

George C. Marshall Space Flight Center

Huntsville, Alabama

prepared by

Univac Division of Sperry Rand Corporation,
Blue Bell, Pa., Norman Goldberg, author

CONTENTS

Heading	Title	Page
	SECTION 1. INTRODUCTION	
	SECTION 2. SUMMARY	
	SECTION 3. MATERIALS AND SAMPLE PREPARATION PROGRAM	
3.1.	Compensation Temperature	3-1
3.2.	Material Preparation	3-3
3.2.1.	Thin Films	3-3
3.2.2.	Polycrystalline Materials.	3-3
3.2.3.	Single Crystals.	3-4
3.3	Sample Preparation	3-5
	SECTION 4. PROPERTIES OF GADOLINIUM ALUMINUM IRON GARNET	
4.1.	Magnetic Measurements.	4-1
4.1.1.	Compensation Temperature	4-1
4.1.2.	Measurement of the Coercive Force.	4-2
4.1.3.	Magnetic Anisotropy.	4-4
4.2.	Optical Measurements	4-5
4.2.1.	Optical Absorption	4-5
4.2.2.	Faraday Rotation	4-6
4.2.3.	Observation of Domains	4-13
4.2.4.	Observation of Bit	4-15
	SECTION 5. THEORETICAL	
5.1.	Optimum Thickness and Wavelength	5-1
5.2.	Power Requirements of Heating Source for Writing	5-2

Heading	Title	Page

SECTION 6. FEASIBILITY MODEL

6.1.	General Features of Model.	6-1
6.2.	Selection of Memory Bit.	6-2
6.3.	Temperature Control of Memory Element. . . .	6-3
6.4.	Amplitude Modulation of the Laser Beam . . .	6-4
6.5.	Testing Procedure.	6-6
6.6.	Results of Test Programs	6-6

ILLUSTRATIONS

Figure	Title	Page
1-1.	Arrangement of Components.	1-2
3-1.	Magnetization of a Typical Rare Earth (Garnet).	3-2
4-1.	Vibrating Sample Magnetometer.	4-2
4-2.	Magnetization Versus Temperature of Three Gadolinium Iron Garnet Samples with Different Aluminum Doping	4-3
4-3.	Coercive Force of Gadolinium Iron Garnet . .	4-3
4-4.	B-H Loops of Gadolinium Iron Garnet.	4-4
4-5.	Magnetic Anisotropy of Gadolinium Iron Garnet.	4-5
4-6.	Optical Absorption of Gadolinium Iron Garnet.	4-6
4-7.	Optical Absorption of GdIG for λ Between 5000 and 8000 Angstroms	4-7
4-8.	Faraday Rotation Measurement Equipment . . .	4-7
4-9.	Faraday Rotation Versus Temperature for Two Drive Fields.	4-9
4-10.	Faraday Rotation Measurement Equipment for Large Fields.	4-10
4-11.	Schematic Diagram of Amplifiers for the Photomultiplier and Lead Sulphide Detectors	4-11
4-12.	Faraday Rotation Versus Wavelength for λ Between 5000 and 8000 Angstroms	4-12
4-13.	β/α Versus Wavelength for λ Between 5000 and 8000 Angstroms.	4-12
4-14.	Equipment for Observing Domains.	4-13
4-1.	Temperature Versus Distance for a Few Different Times	5-3
6-1.	Block Diagram of System.	6-1
6-2.	Top View, Mechanical and Optical Assembly. .	6-3

Figure	Title	Page
6-3.	Temperature Control Unit	6-4
6-4.	Drive Circuitry for the Modulator.	6-5
6-5.	Power Output of Modulator as a Function of Voltage.	6-6
6-6.	Block Diagram of Testing System.	6-7
6-7.	Timing Diagram	6-8

SECTION I

INTRODUCTION

This is the final report of Contract NAS8-20509. The goals of this program were threefold:

1. To develop the sample material and the techniques of sample preparation required for a room-temperature magneto-optic memory.

2. To study the magnetic, optical, and thermal properties of these materials in order to optimize the design of a magneto-optic memory.

3. To design and build a magneto-optical memory for demonstrating packing density and read and write cycle times.

The storage element of the proposed memory is a platelet of gadolinium iron garnet (GdIG) doped with aluminum so that the compensation temperature is approximately room temperature. Information is written into this memory by simultaneously heating a discrete area of the sample and applying a magnetic field. The coercivity of the gadolinium iron garnet is very large at the compensation temperature. The applied field is larger than the coercivity of the heated region, but not the remainder of the sample. Therefore, the magnetic moment of only the heated region is switched into the direction of the applied field. The readout signal is derived from the Faraday rotation of a polarized beam of light by the sample. The state of magnetization of a region is determined by observing the direction of Faraday rotation. Figure 1-1 shows the arrangement of the various components.

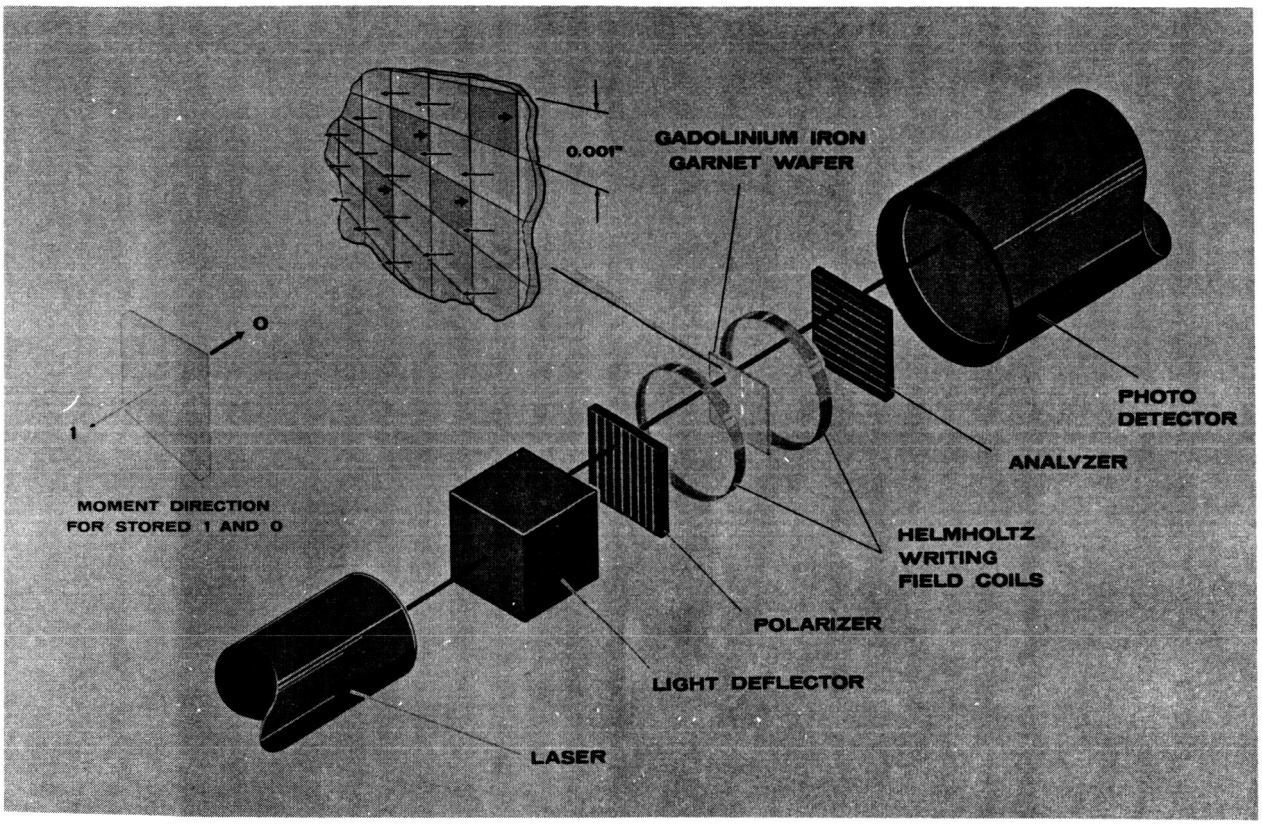


Figure 1-1. Arrangement of Components in a Magneto-Optic Memory System

SECTION 2

SUMMARY

We have developed the techniques of growing large flux-free GdIG with a compensation temperature of 25°C. The method of preparing platelets of GdIG suitable for use as a memory element has been established.

Faraday rotation and absorbtion measurements have been made over a wide range of wavelengths, and the optimum wavelength for memory operation has been determined.

We have recognized the importance of domain walls on the minimum size of a bit on a continuous platelet; we have therefore scribed our samples and achieved square bits 20 microns on a side. The optimum procedure for heating the sample during the write cycle as well as the laser power required has been determined. Writing speeds of a few microseconds are possible with a 100-milliwatt laser if all 0's are written at one time followed by all the 1's.

Finally, a system has been built which demonstrates the feasibility of the GdIG memory element. Memory bits were 20 microns on a side. The heating time was found to be 1 millisecond, which is consistent with our theoretical conclusions.

The GdIG memory element can be improved by using an argon ion laser with an output at 5145 Angstroms, by making the scribed lines opaque, and by using a beam expander and thereby achieve better focusing of the laser beam.

SECTION 3

MATERIALS AND SAMPLE PREPARATION PROGRAM

3.1. COMPENSATION TEMPERATURE

The first goal of this project was the preparation of a material with a compensation temperature of 25°C. It was determined that such a material could be made by replacing a small fraction of the iron ions in gadolinium iron garnet with aluminum ions. The effect of the aluminum can be understood from the following discussions.

In the gadolinium iron garnet, $Gd_3Fe_5O_{12}$, the iron ions occupy two different sites. Three of the atoms in each formula unit occupy tetrahedral sites, and the other two occupy octahedral sites. The iron ions on the octahedral and tetrahedral sites are coupled antiferromagnetically by the super-exchange mechanism; that is, the coupling is by way of the intervening oxygen. The total magnetization of the ions on the tetrahedral sites is 1.5 times as large as the moment on the octahedral sites, and therefore the resultant magnetization of the iron ions is in the direction of the magnetization of the ions in tetrahedral co-ordination. The gadolinium ions are coupled antiferromagnetically to the net moment of the iron ions. The coupling is much weaker than that between the iron ions. As a consequence the magnetization of the rare earth ions drop very quickly with increasing temperature, approximately as 1/T. Therefore, at temperatures near the Curie point, the magnetization of the iron ions dominate. On the other hand, because the gadolinium has a saturation moment which is much larger than the resultant magnetization of the iron ions, the moment of the gadolinium ions dominate at low temperature. Therefore, a compensation point of the magnetization is observed.

Figure 3-1 shows a plot of the magnetization of the iron ions and a typical rare earth ion as a function of temperature. Also shown is the

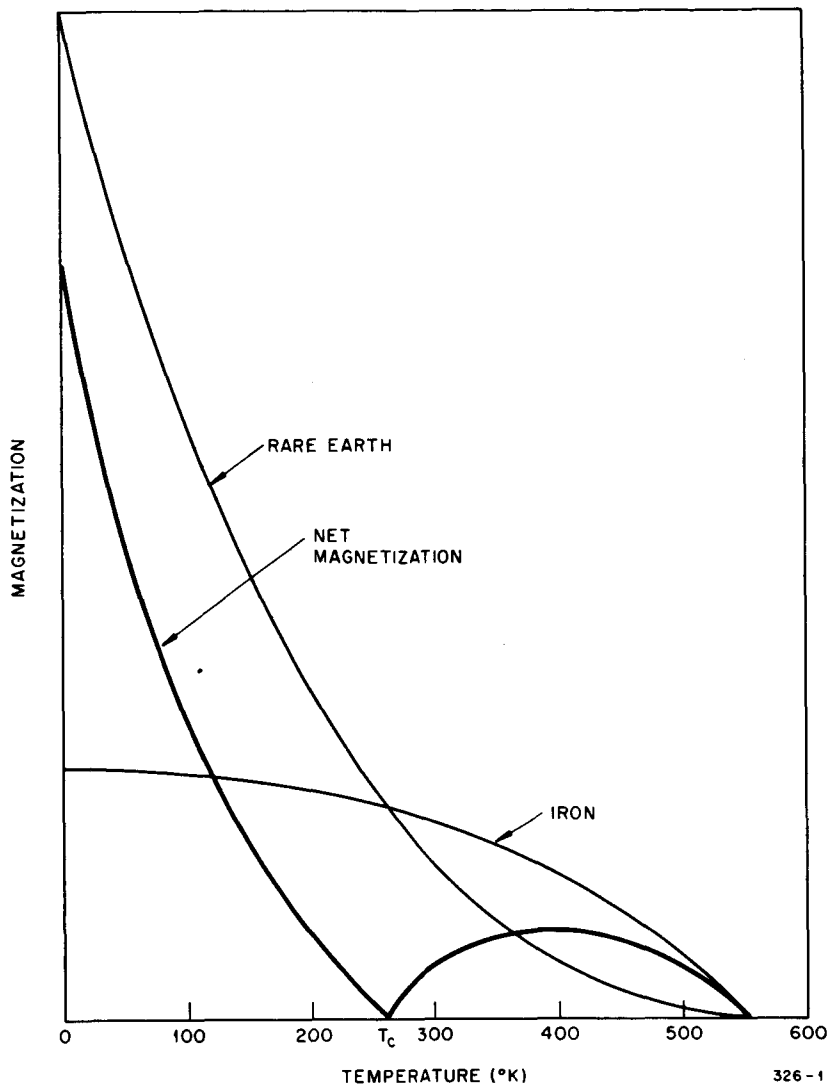


Figure 3-1. Magnetization of a Typical Rare Earth (Garnet)

total magnetization. At the temperature marked T_c, the magnetization of the iron and rare earth ions cancels.

The compensation temperature of gadolinium iron garnet is $15^{o}C$. The substitution of aluminum for the iron reduces the moment of the iron lattice. This is a consequence of the preferential occupation of tetrahedral sites by the aluminum because the aluminum ion is smaller than the iron ion, and the tetrahedral sites are smaller than the octahedral sites. A reduction of the magnetization of the iron lattice raises the temperature at which the iron lattice is compensated by the gadolinium lattice.

The program to raise the compensation temperature was carried out on single crystals. In the first run, four percent of the Fe_2O_3, used in the crystal growing mixture, was replaced by Al_2O_3. (Details of the crystal growing procedure are presented under heading 3.2.3). The compensation temperature of the resulting crystals was 60^oC. The composition of these crystals was chemically determined to be $Gd_3Fe_{5-x}Al_xO_{12}$ where x was 0.03. Additional runs were made with different amounts of aluminum, and crystals were grown with compensation temperatures of 17^oC, 30^oC, and 27^oC. It was found that an x = 0.02 in the above formula resulted in crystals with a compensation temperature very close to room temperature.

3.2. MATERIAL PREPARATION

Three different methods of preparing gadolinium iron garnet were investigated: thin films, polycrystalline samples, and single crystals.

3.2.1. THIN FILMS

Efforts were made to prepare galolinium iron garnet films by the method described by Wade, et al.[1] In this procedure, stoichiometric mixtures of gadolinium, iron, and aluminum nitrate in solution are prepared first. Quartz substrates are coated with the solution and dried at 400^oC. About 10 coats are applied. The substrate is then fired in a pure oxygen atmosphere at 1100^oC for two hours.

The results were disappointing. The films were very non-uniform. X-ray diffraction measurements were made, and it was found that the films were not single phase. Magnetic measurements showed a compensation temperature of about 40^oC, however the magnetization did not drop to zero at the compensation temperature. This shows that there is more than one magnetic component.

In retrospect, this effort was exceedingly premature. In view of the primitive state-of-the-art of this type of memory, it is advisable to perform all research on the very best material, namely single crystals.

[1]Wade, W., Collins, T., Malinofsky, W. W., and Skudera, W., J. Appl. Phys., 34, 1219 (1963).

3.2.2. POLYCRYSTALLINE MATERIALS

Gadolinium iron garnet samples were made by Sperry Microwave in Clearwater and prepared for optical studies. Although the work with polycrystalline material was limited, a number of significant conclusions were reached. Very dense, highly uniform polycrystalline material could be prepared. The optical absorption and the Faraday rotation of the polycrystalline material were essentially the same as those of the single-crystal material. Polycrystalline samples could not be made as thin as the single-crystal samples. The thinnest sample achieved was 7×10^{-3} centimeters thick, which is more than twice the optimum thickness for use with a helium-neon laser. And finally, the most serious defect, the polycrystalline samples did not have a magnetic ansisotropy; therefore, the direction perpendicular to the plane of the platelet could not be made into an easy direction.

3.2.3. SINGLE CRYSTALS

Single-crystal material was grown by the molten flux method.[2] In this method one mixes all the constituents of the material with a flux, the mixture is then raised to a temperature at which the flux is in the liquid state, and all the constituents are dissolved. One then reduces the temperature slowly. When the solution is cooled below the temperature at which it is saturated, crystals nucleate on microscopic impurities and then grow as the temperature is reduced.

In our work, platinum-rhodium crucibles were required to contain the mixture because of its corrosive nature at high temperatures. Useable crystals with a mass between 1 to 8 grams were grown in a 100-milliliter crucible. If larger crystals are desired, a 1000-milliliter crucible can be used. The constituents that yielded a garnet with a 27-degree compensation temperature were:

Gd_2O_3	10 mole percent, weight = 36.18 grams
Fe_2O_3	19.6 mole percent, weight = 31.20 grams

---

[2] Kriessman, C. J., and Goldberg, N., "Preparation and Crystal Synthesis of Magnetic Oxides," in Magnetism, Vol 3, Ed. Rado, G. T., and Suhl, H., (Academic Press, Inc., 1963), pp. 553—597.

Al_2O_3	0.4 mole percent, weight = 0.40 gram
PbO	3 mole percent, weight = 69.96 grams
PbFl	40 mole percent, weight = 98.0 grams

The lead oxide and lead fluoride are the flux or solvent.

The mixture is preheated at 120°C for one hour to drive off moisture, and then a platinum cover is tamped on to reduce evaporation. The platinum crucible is placed in a heavy Z_rO_2 crucible to protect the furnace in case of a leak in the platinum crucible. It has been found that larger crystals are grown if there is a temperature gradient in the crucible. To ensure a temperature gradient in the crucible it is positioned assymetrically. The furnace is heated to a temperature of 1270 degrees and kept there for at least six hours. The furnace is then cooled at a rate of about 2°C per hour to approximately 1000°C, at which time the power is shut off, and the crucible is furnace cooled to room temperature. The crystals are removed from the solid lead oxide-lead fluoride matrix by repeated boiling in 50 percent HNO_3. A typical run would yield material for making 10 to 20 samples.

3.3. SAMPLE PREPARATION

It is necessary to prepare samples that are thin enough to transmit a significant fraction of the light. It is shown under heading 5.1 that maximum Faraday rotation signals are obtained for samples which reduce the intensity of the incident light by a factor of e^2. The optimum thickness therefore depends on the wavelength of light that is used. If a helium-neon laser is used at 6328 Angstroms, the optimum thickness is about 1 mil.

Developing the technique for preparing platelets of this thickness was a major effort. We have previously reported a procedure which could be used to make samples that were thin enough, but the samples had a serious defect. They were mounted in epoxy and it depolarized the light and thereby reduced the Faraday rotation signal.

We have now developed the following new procedure, which avoids this difficulty.

1. Orient crystals so that they can be cut along a [111] plane.
2. Cut the crystal into 20-mil sections with a 15-mil diamond saw.
3. Shape slabs into squares and mount in epoxy.

4. Remove 5 to 10 mils of material with 400 grit SiC paper to eliminate all sawing damage.

5. Grind off about 2 mils on 600 grit SiC paper so that all cold work damage from the 400 paper is removed.

6. Rough-polish sample on a 250-revolution-per-minute nylon lap using SnO_2 and distilled water until no scratches are visible with a 14-power lens.

7. Final-polish on a 125-revolution-per-minute duracloth lap using 0.1 micron gamma Al_2O_3 and water with medium to light pressure for about 10 minutes.

8. Carefully remove epoxy from sample. This is done by grinding away most of it and then using an epoxy solvent to complete the removal.

9. Mount the polished sample face down onto a 7-millimeter square optical glass which is 50 mils thick. An optical thermosetting plastic, No. 70 C, made by H. Courtright and Co., Chicago, Ill., was used to cement the GdIG to the glass.

10. Encapsulate the glass-mounted sample in epoxy and repeat the previously described polishing.

11. Carefully remove epoxy.

After the samples have been polished, they are scribed into squares. This is done with a Model 750 Scriber made by Kulicke and Soffa, Fort Washington, Pa. A "dead sharp" diamond phono needle with about 10 grams force has been used to scribe squares which were 20 microns on a side. The memory does not operate properly if the scribe line does not cut completely through the sample. This behavior is explained under heading 4.2.4.

SECTION 4

PROPERTIES OF GADOLINIUM ALUMINUM IRON GARNET

In order to design a memory based on gadolinium aluminum iron garnet, measurements of certain magnetic and optical properties of this material are essential. This section describes the measurements made and the techniques used in making the measurements.

4.1. MAGNETIC MEASUREMENTS

4.1.1. COMPENSATION TEMPERATURE

The determination of the compensation temperature was made with the aid of a vibrating sample magnetometer. Figure 4-1 shows a diagram of the device. The sample is vibrated at 90 cycles per second normal to the d.c. magnetic field of a 4-inch Varian magnet. The field is large enough to saturate the magnetization of the sample. The motion is provided by an 1800-revolution-per-minute synchronous motor, a 1 to 3 speed changer, and an eccentric cam to transform the rotary motion to reciprocal motion. The amplitude of the motion is typically 1 millimeter. The magnetization is sensed by a pick-up coil whose axis is parallel to the axis of the sample motion. The amplitude of the a.c. signal generated in the coil is therefore proportional to the magnetization.

Because of the small magnetization of our samples, (zero at the compensation temperature) it is necessary to use a lock-in amplifier to increase the signal-to-noise ration. A reference signal is generated by a small permanent magnet which is also vibrated at 90 cycles per second. The samples are immersed in an oil bath whose temperature can be controlled. Figure 4-2 shows plots of magnetization (arbitrary units) versus temperature of three different samples. The temperature at which the magnetization is minimum is the compensation point.

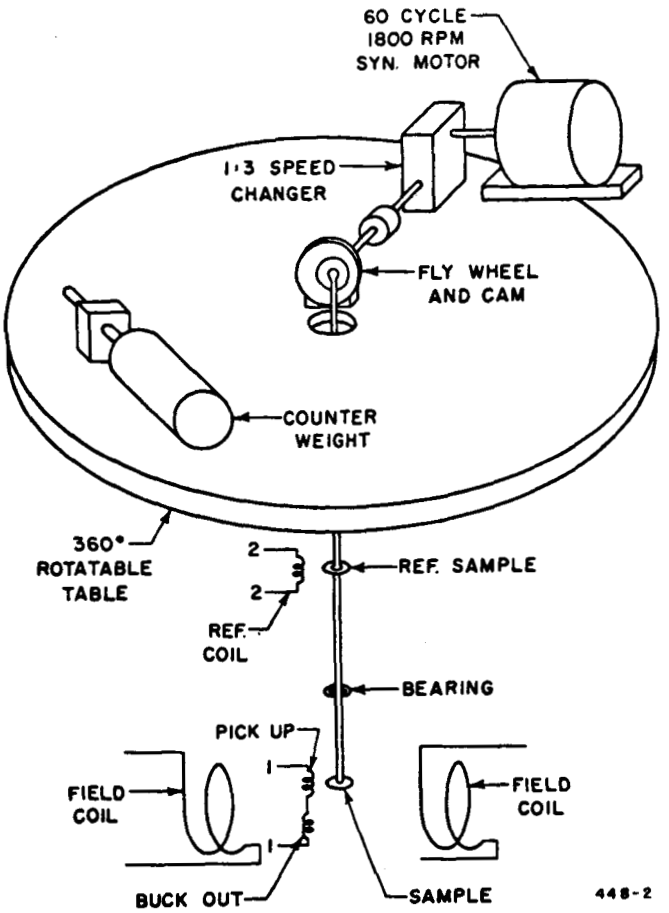


Figure 4-1. Vibrating Sample Magnetometer

4.1.2. MEASUREMENT OF THE COERCIVE FORCE

The coercive force, H_c, is another important magnetic parameter in the design of the magneto-optic memory. It was also measured with the vibrating magnetometer. The sample and pick-up coil were positioned on a line parallel to the field direction, and therefore the amplitude of the a.c. signal generated in the coil is proportional to the component of the magnetization parallel to the field. The field at which the magnetization reversed sign is H_c. It was directly plotted on an x-y recorder versus temperature. A typical plot is shown in Figure 4-3.

Figure 4-4 shows a series of B-H loops at different temperatures. These loops graphically illustrate the changes in the sample as its temperature is changed. The drive field for each of these curves was identical. Far from the compensation point the magnetization is largest, therefore the height of the loop is largest. At the compensation point the coercive force is

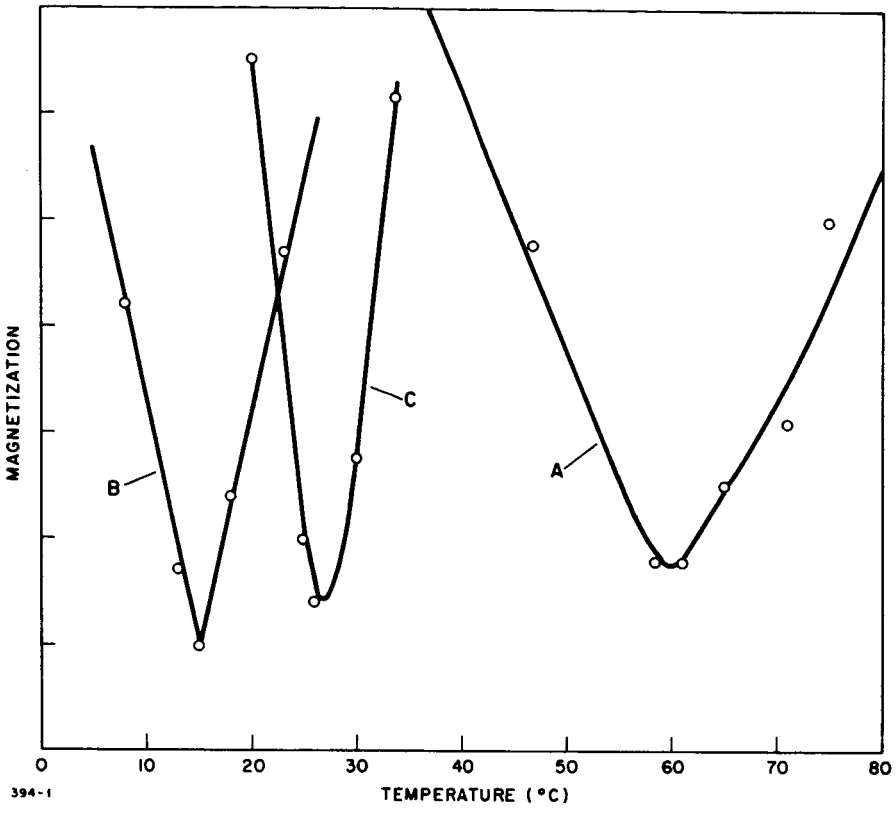


Figure 4-2. Magnetization Versus Temperature of Three Gadolinium Iron Garnet Samples with Different Aluminum Doping

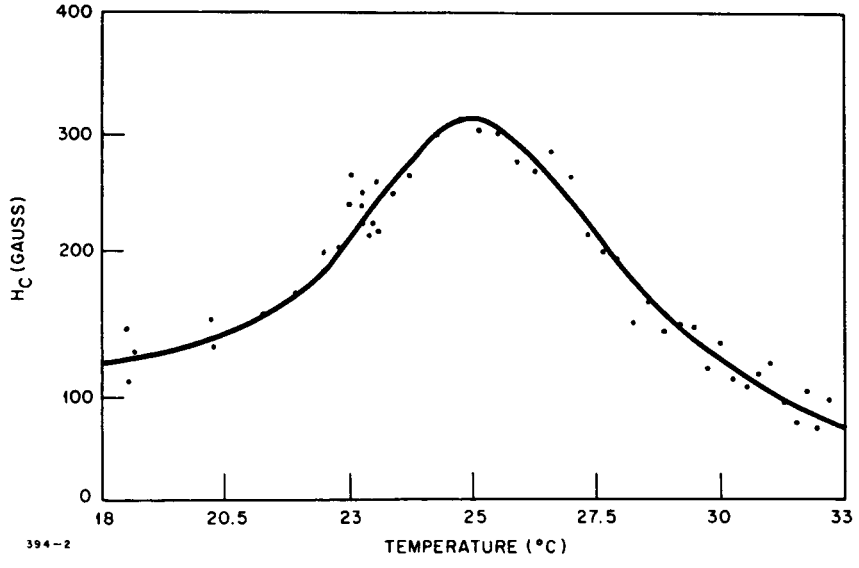


Figure 4-3. Coercive Force of Gadolinium Iron Garnet

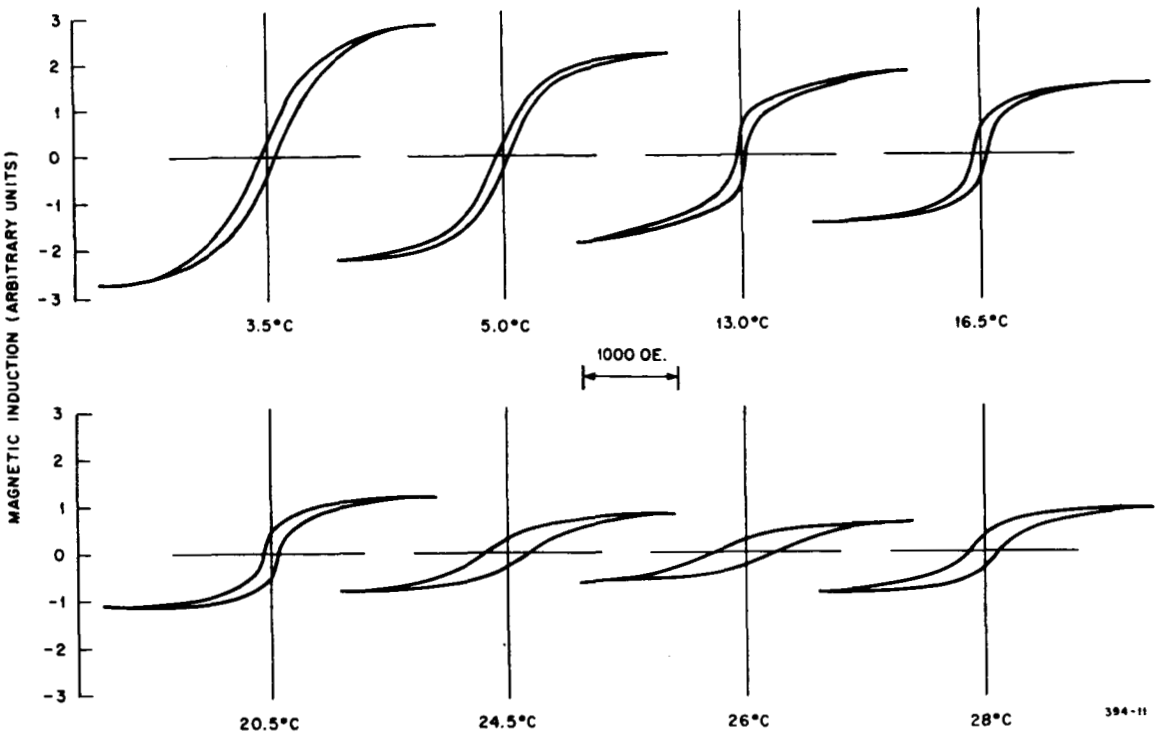


Figure 4-4. B-H Loops of Gadolinium Iron Garnet

largest, and this is reflected in the large width of curve at zero magnetization near the compensation point.

These results have an important bearing on the temperature stability of the memory. For example, if one planned to write by heating a bit $6^{o}C$ above the compensation temperature, a field of 75 oersteds would be required to switch the heated area. This field would not affect the unheated portion of the platelet as long as the temperature was maintained within $6^{o}C$ of the compensation temperature. The sharper this peak is, the more easily it will be to write in this memory. However, a sharp peak also requires better temperature stability. It is felt that in the early period of the development of this memory, ease of writing supersedes temperature stability.

4.1.3. MAGNETIC ANISOTROPY

A check on the alignment of the sample can be made by a magnetic anisotropy measurement. The samples should be aligned along the [111] direction. An anisotropy measurement made by rotation around this axis should show a three-fold symmetry. Figure 4-5 is a plot of an anisotropy measurement. The lack of three-fold symmetry definitely shows that it was not properly oriented. Subsequent samples were oriented in the [111] direction.

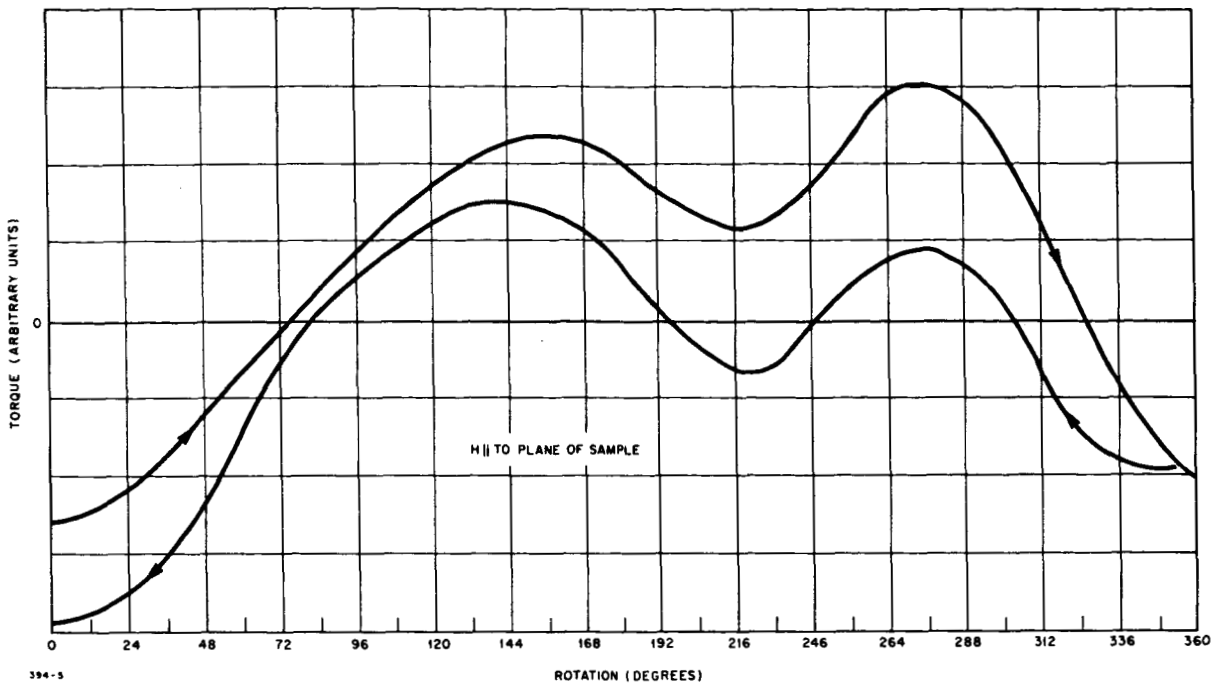


Figure 4-5. Magnetic Anisotropy of Gadolinium Iron Garnet

4.2. OPTICAL MEASUREMENTS

4.2.1. OPTICAL ABSORPTION

The optimum wavelength for the operation of a magneto-optic memory depends on both the Faraday rotation constant and the absorption. This topic is discussed in detail under heading 5.1. The essential results are that the optimum thickness is $2/\alpha$ where α is the absorbtion constant and that the optimum wavelength is the wavelength where β/α is maximum where β is the Faraday rotation per unit length.

Therefore measurements of α and β as a function of wavelength were undertaken. The absorbtion measurements were made with a Cary spectrophotometer No. 14. Both single-crystal and polycrystalline samples were examined, and the results were essentially the same for both samples. A typical run is shown in Figure 4-6. The sample used only permitted measurements of wavelengths longer than 7000 Angstroms. For wavelengths shorter than this the absorption was so large that a detectable amount of light was not transmitted.

To examine the region between 5000 Angstroms and 7000 Angstroms, a very thin sample was prepared. The results are shown in Figure 4-7.

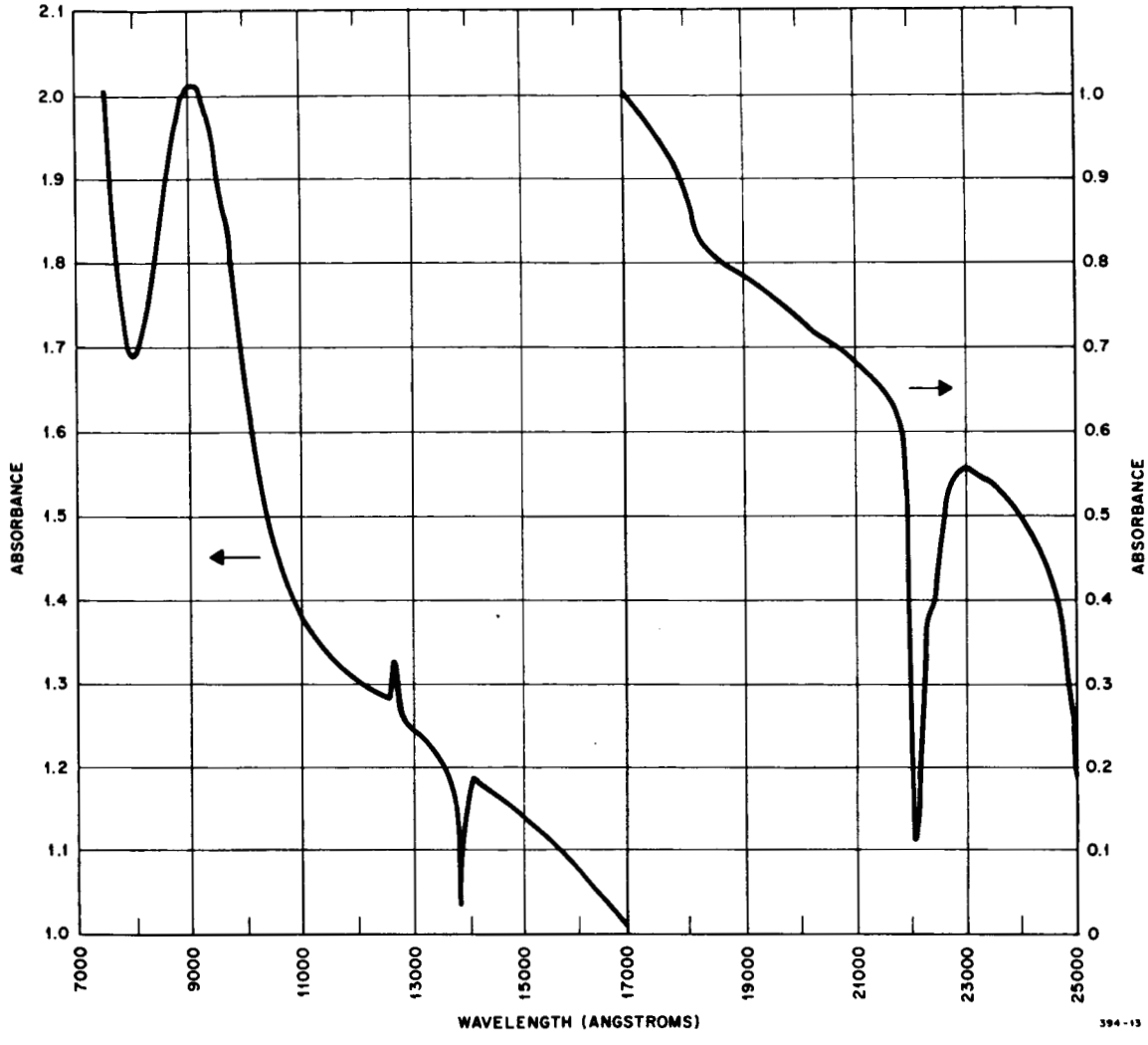


Figure 4-6. Optical Absorption of Gadolinium Iron Garnet

4.2.2. FARADAY ROTATION

Faraday rotation measurements were made using a helium-neon laser source. A schematic drawing of the setup is shown in Figure 4-8. The laser beam is chopped at 90 cycles per second. It passes through a Glan-Thompson polarizer, the sample, a Glan-Thompson analyzer, and is then detected by a 1P28 photo-multiplier. The laser beam out the back end is detected by a photo-transistor, and this signal is used as a reference signal for the lock-in amplifier. It is also used as a bucking signal in the difference amplifier and phase adjust network and is set so that in one of the polarization states there is no signal.

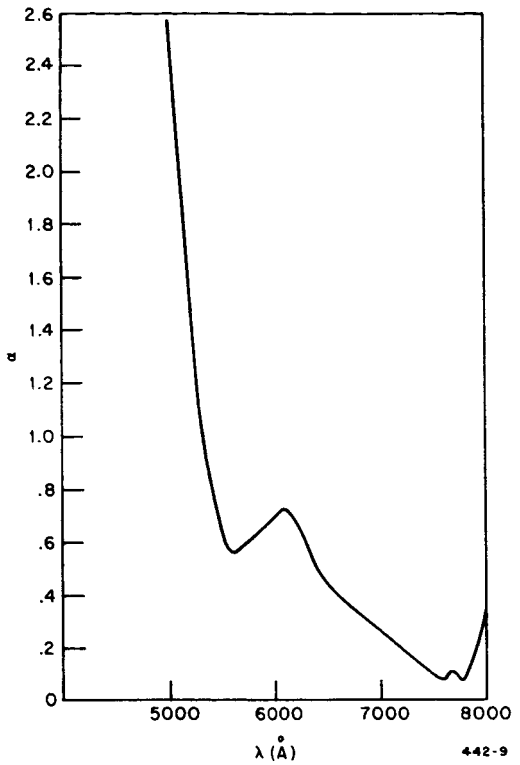


Figure 4-7. Optical Absorbtion of GdIG for λ between 5000 and 8000 Angstroms

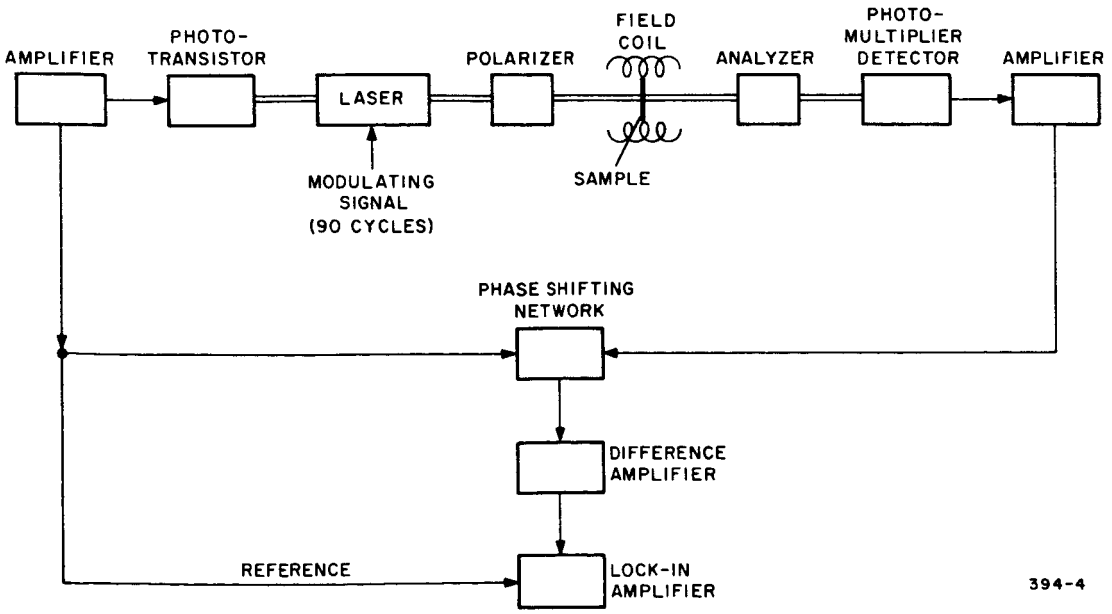


Figure 4-8. Faraday Rotation Measurement Equipment

Additional sensitivity was achieved by detecting the change in the signal when the extinction axis of the analyzer is set at 45 degrees to the plane of polarization of the light incident on it rather than parallel to it. The reason for the improved sensitivity can be understood from the following discussion.

The intensity of polarized light transmitted by an analyzer is $I_o \sin^2\theta$, where I_o is the intensity of the incident light and θ is the angle between the direction of the polarization of the incident light and the extinction axis of the analyzer. The rate of change of intensity with a rotation of the plane of polarization is proportional to the sensitivity and is given by

$$\frac{dI}{d\theta} = 2I_o \sin\theta \cos\theta = I_o \sin 2\theta$$

Therefore, the maximum sensitivity occurs at $\theta = 45$ degrees. The improvement over setting the analyzer at the extinction angle can be very large.

We have made Faraday rotation measurements on a number of samples as a function of the temperature. The measurements were made as follows: A field of 300 oersteds is applied momentarily along the direction of the incident light to align the magnetization. The output of the detection system is zeroed by an out-of-phase signal from a second detector. A field of 10 oersteds or 20 oersteds is then applied in the reverse direction, and the change in the output, which is proportional to the change of the Faraday rotation, is recorded. These are the signals of interest for memory applications rather than the larger signals observed while the magnetization is changed from saturation in one direction to saturation in the other.

The results of a typical set of measurements are shown in Figure 4-9. From these curves one can see that the temperature stability depends on the magnetic field used for writing. With a field of 10 oersteds, there was no rotation for a range of about 6^oC. For a 20-oersted field, the temperature range for which there was no rotation was reduced to about 3^oC.

The equipment described above was deficient in a number of respects. First, the maximum field that could be applied was not sufficient to saturate the sample at all temperatures. Second, the application of the field heated the sample. A completely new set-up has been build which replaces the

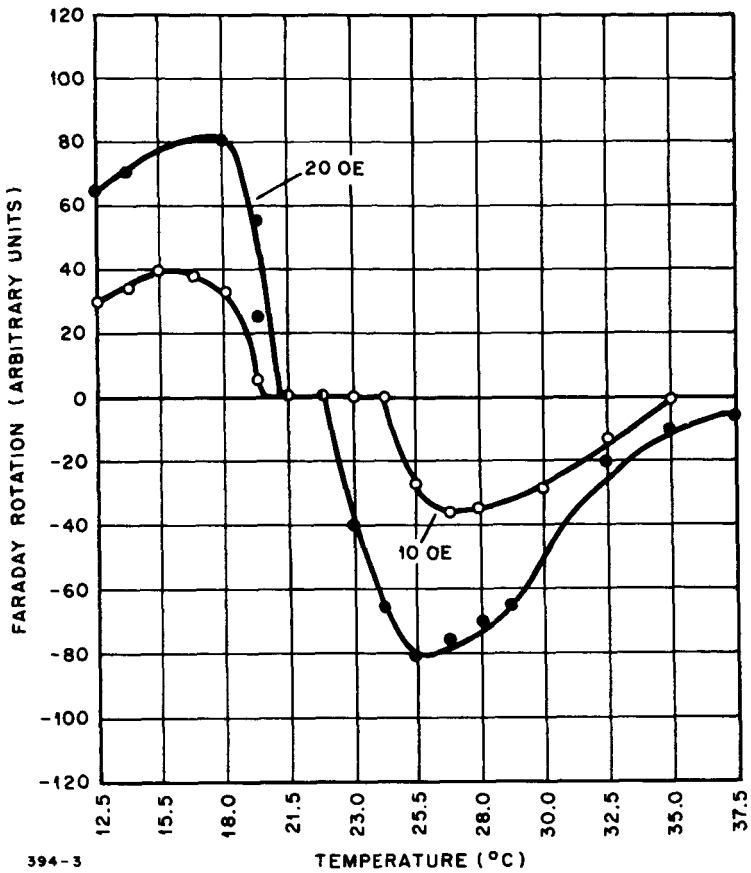


Figure 4-9. Faraday Rotation Versus Temperature for Two Drive Fields

Helmholtz coils with the Varian 4-inch magnet. In addition, the system uses a tungsten lamp and a monochromater as the light source. The light is mechanically chopped by a rotating disc and is then polarized by a Glan-Thompson prism. It then passes through the sample which is positioned between the poles of a 4-inch Varian magnet. The light passes through a second Glan-Thompson prism and is then detected. A photomultiplier is used as the detector for wavelengths less than 9000 Angstroms, and a lead sulphide detector is used for light with a wavelength larger than 9000 Angstroms. With the large signals that are obtained with our new samples, it should not be necessary to use a lock-in amplifier for detection. A complete sketch of the equipment is shown in Figure 4-10. A schematic of the amplifier for the lead sulphide and photomultiplier detectors is shown in Figure 4-11. Measurements of the saturation Faraday rotation as a function of temperature and wavelength have been made with this equipment.

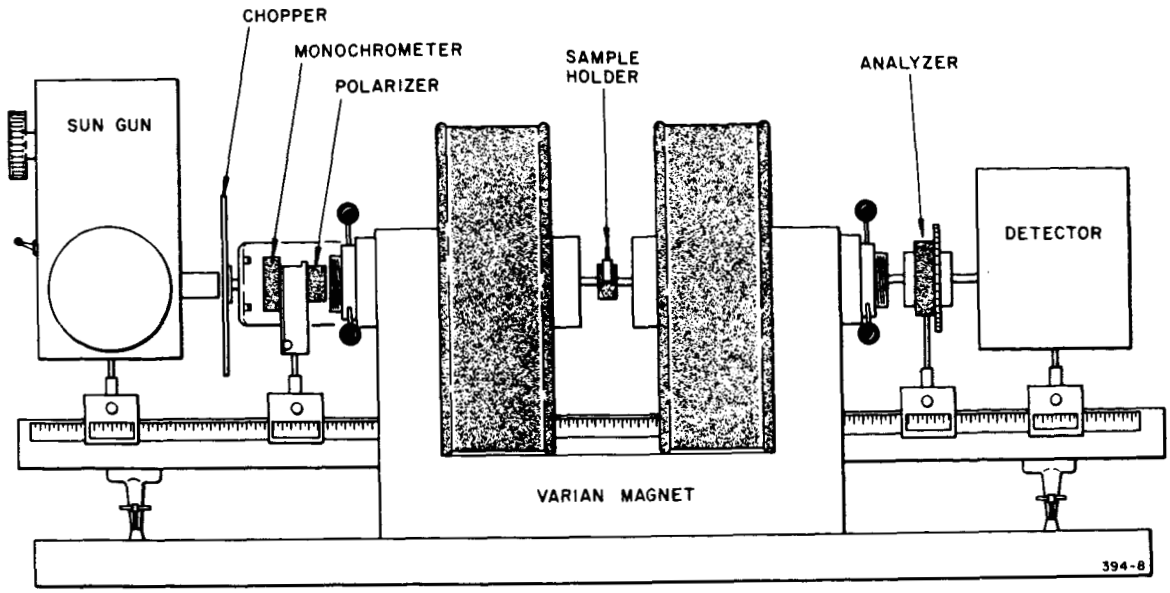
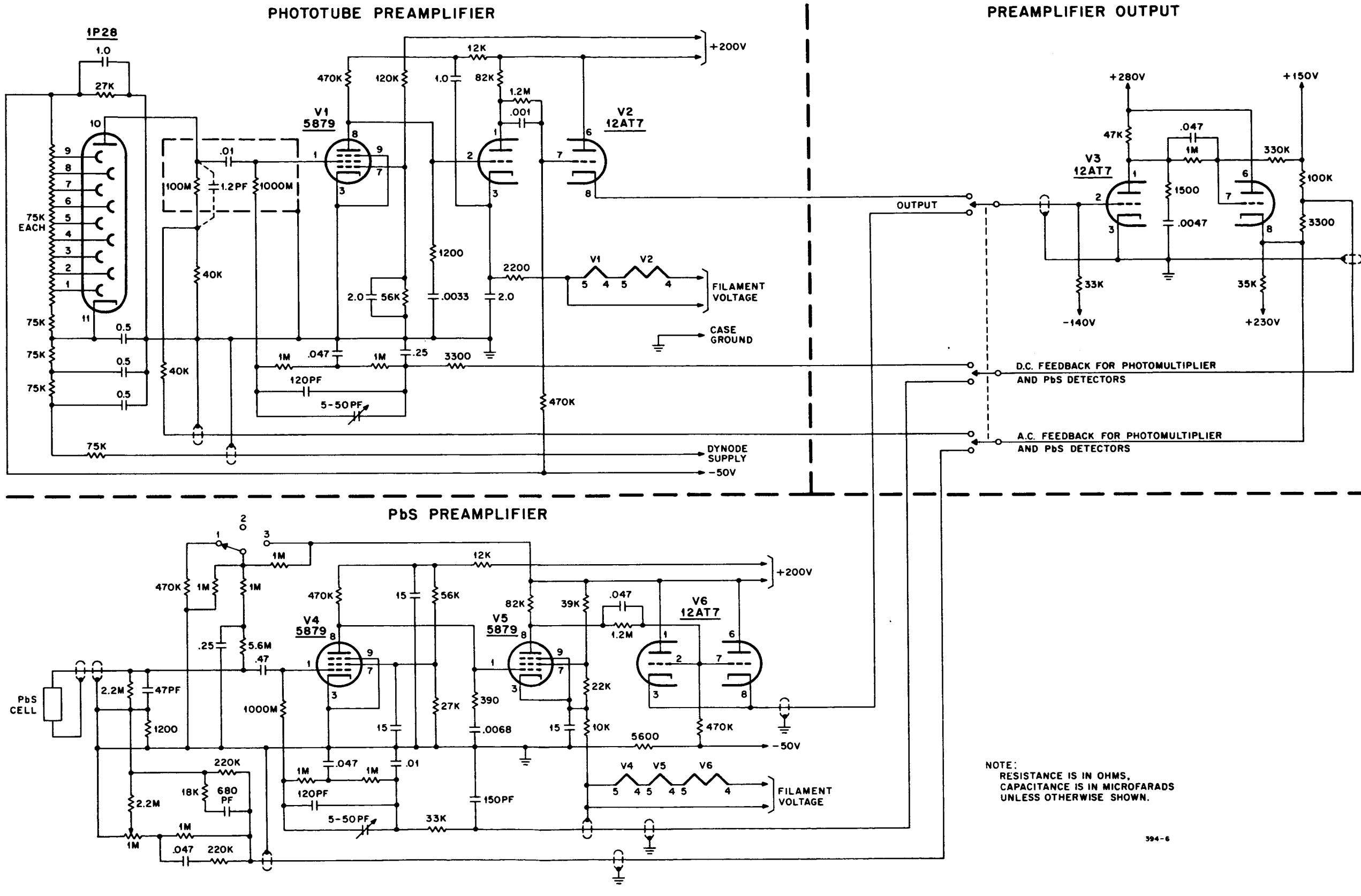


Figure 4-10. Faraday Rotation Measurement Equipment for Large Fields

The results for the Faraday rotation measurements are shown in Figure 4-12. In Figure 4-13 we have plotted the ratio of the Faraday rotation to the absorbtion constant versus wavelength. A large value of β/α yields a large signal. A number of conclusions can be drawn from this figure. First, the He-Ne laser with an output at 6330 Angstroms is a very undesirable light source for the GdIG memory. Second, the optimum wavelength is longer than 7000 Angstroms; third, if smaller wavelengths are desirable, 5600 Angstroms is the best choice.

A smaller wavelength is desirable because the optimum thickness decreases with a decrease in wavelength, and a thinner memory element has a number of advantages. First, the power requirements for heating during the writing operation are reduced. Second, the time for a heated bit to return to the compensation temperature is reduced, and this time is the lower limit for the writing speed. Third, it is easier to scribe a sample into small segments if it is thinner.

After a survey of the available laser, we have decided that an argon ion laser operating at 5145 Angstroms is the best choice. Using Dillon's results for the absorbtion coefficient α we find that the optimum thickness for the operation of a memory at 5145 Angstroms is 10 microns. A 10-micron thickness can be achieved with our present techniques, and it seems to be a reasonable choice.



NOTE:
RESISTANCE IS IN OHMS,
CAPACITANCE IS IN MICROFARADS
UNLESS OTHERWISE SHOWN.

394-6

Figure 4-11. Schematic Diagram of Amplifiers for the Photomultiplier and Lead Sulphide Detectors

4-11-1

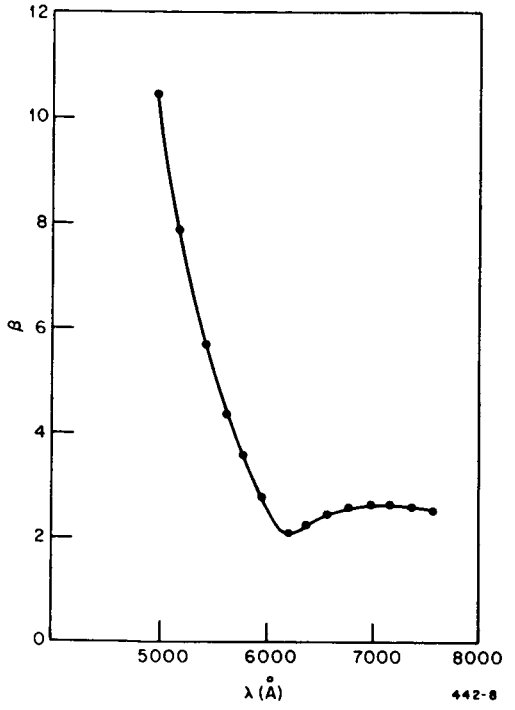


Figure 4-12. Faraday Rotation Versus Wavelength for λ Between 5000 and 8000 Angstroms

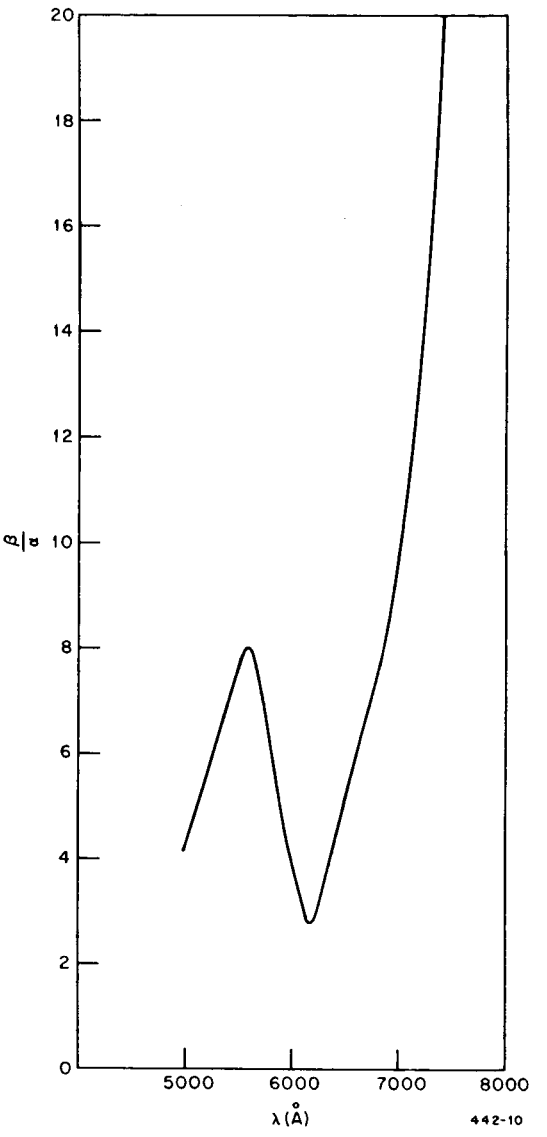


Figure 4-13. β/α Versus Wavelength for λ Between 5000 and 8000 Angstroms

4.2.3. OBSERVATION OF DOMAINS

A setup which has been built for visually observing domains in a garnet is shown schematically in Figure 4-14. The laser is not used in this setup. The sample is positioned between a pair of Helmoltz coils and is

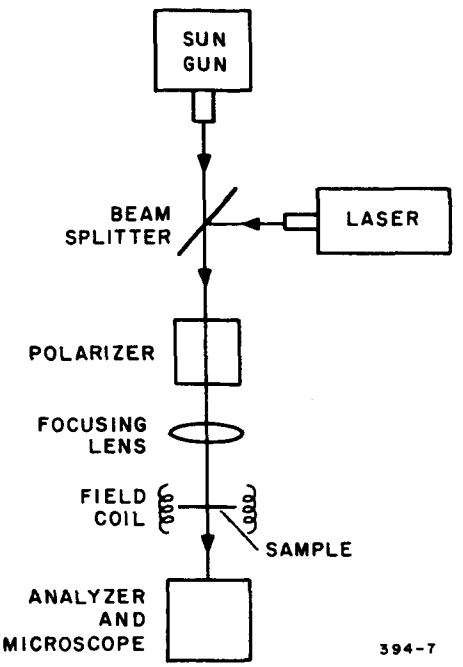


Figure 4-14. Equipment for Observing Domains

mounted on the stage of a polarizing microscope. The temperature of the sample can be controlled. The light from a sun gun is polarized, transmitted through the sample, and then into the objective of the microscope. Domains are clearly visible with this setup because the transmission of the sample depends on the direction of the magnetization. There is a spectacular change in color from red to yellow as the domains are switched, and the contrast is much better than that of Kerr Effect or Bitter Pattern equipment.

Figure 4-15 shows some typical black and white photographs of the domain configuration after a large field is applied to saturate the sample and is then removed. Near the compensation temperature the domains tend to be large while far from the compensation temperature the sample breaks up into a complicated maze pattern.

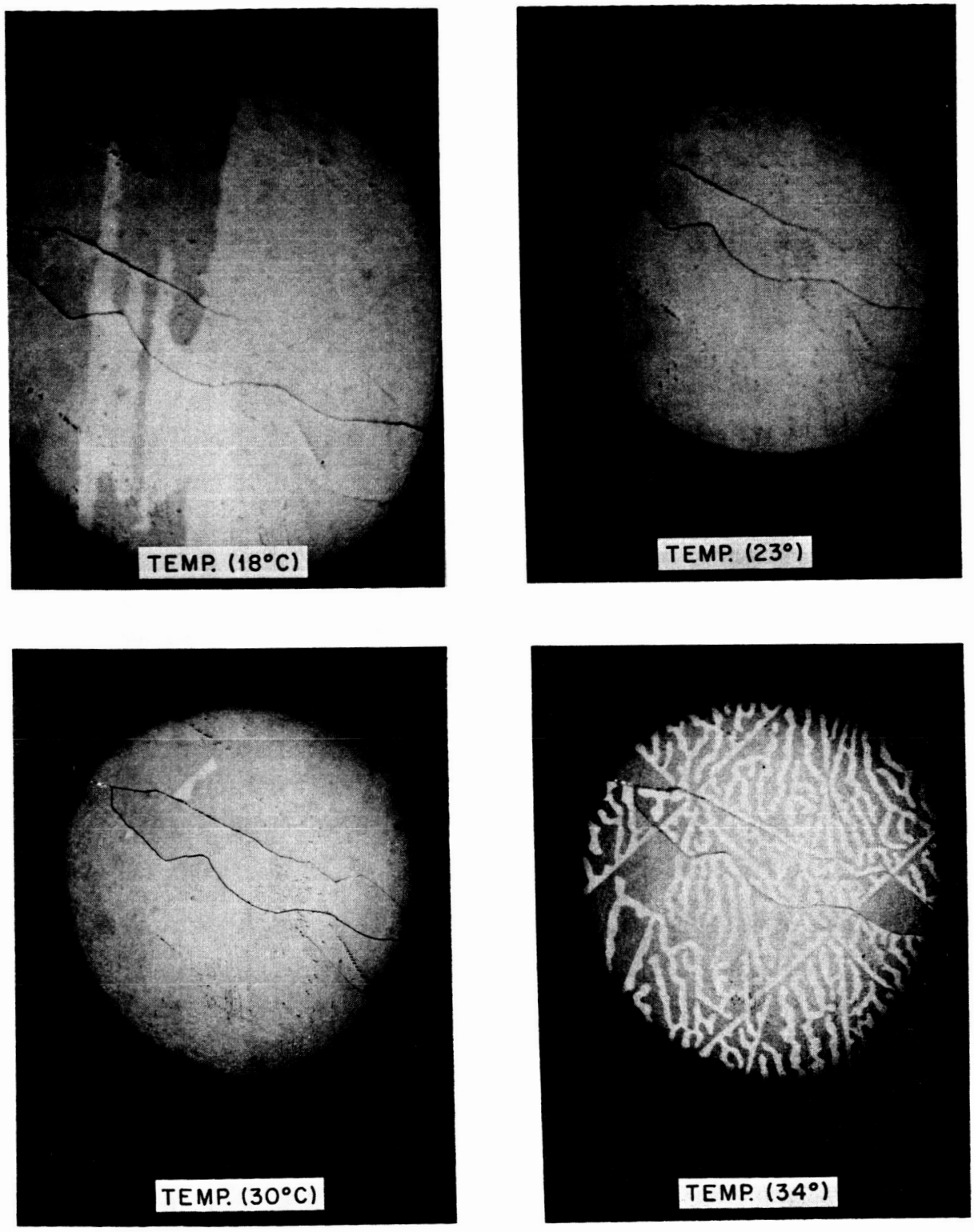


Figure 4-15. Domain Patterns Observed by Faraday Rotation

The compensation temperature and the coercive force can be determined with this equipment. The field necessary to saturate the sample (H_s), and the minimum field required to initiate a reversed domain (H_c), as a function of temperature, is shown in the following table. It can be seen that at the compensation temperature ($19^{o}C$ for this sample) the coercive force is a maximum and is equal to 140 oersteds.

Temperature (^{o}C)	H_s (oersted)	H_c (oersted)
0	60	6
5	66	5
9	66	14
11	70	16
14	180	30
17	300	60
18	400	70
19	> 500	140
20.5	100	40
22.5	100	40
24	50	20

At the compensation temperature the field to saturate the sample is also a maximum.

4.2.4. OBSERVATION OF A BIT

Equipment has been built for the observation of a bit and is shown schematically in Figure 4-14. The procedure used is the following: The temperature of the sample is maintained at the compensation point. A magnetic field large enough to saturate the sample perpendicular is applied. The saturation can be observed by viewing the sun-gun light transmitted through the sample. After the sample is saturated, a reverse field of 20 oersteds is applied. This field is not large enough to initiate a reversed domain for material whose temperature is maintained near the compensation point. However, it will flip the magnetization of that portion of the sample which is heated about 5 degrees above the compensation temperature. A small area (approximately 10 microns) is heated by a 10-milliwatt helium-neon

laser. The flipped region can be detected by a change in the intensity of the light from the sun-gun transmitted through the flipped region. A calculation of the required intensity and time of the laser pulse has been made and is presented under heading 5.2.

Using the procedure described above, we were able to switch small regions of the platelet and observe the switched area. However, the smallest area that can be switched on a continuous platelet is about 10^{-2} centimeters. Also, the size and shape of the switched region could not be controlled. Thus, the maximum packing density of a continuous platelet is severely limited.

The following discussion explains the large minimum size of a bit on a continuous sheet.

Consider a portion of the sample of thickness t and radius r which has been heated above the compensation temperature so that it has a magnetization M. An application of a field H in the direction opposite to that of the magnetization will tend to rotate the magnetization of the heated portion of the sample. A 180° rotation of the magnetization reduces the energy of the sample $2MHV = 2MH\pi r^2 t$, where V is the volume of the sample and r is the radius of the switched region. There is another energy change; a domain wall is formed between the switched region and unswitched regions, and its presence increases the energy of the sample. The energy of the wall is $\Sigma A = \Sigma 2\pi rt$ where Σ is the wall energy per unit area and A is the area of the wall. For extremely small areas the increase in energy from the creation of the domain wall would be larger than the decrease in magnetic energy, and therefore the magnetization is not switched. The minimum size of a bit is the value of r for which the wall energy equals the magnetic energy.

$$2\pi r^2 tMH = 2\pi rt\Sigma$$

$$r = \frac{\Sigma}{MH}$$

The wall energy has been estimated from the relation[1]

$$\Sigma = 2(KA)^{\frac{1}{2}}$$

[1] C. Kittel, Rev. Mod Phys. 21, 541 (1949).

where K is the anisotropy energy and A is the exchange energy, and was found to be 0.13 ergs/cm^2. To estimate r, we assume a value of 1 gauss for M, which corresponds to heating the sample 5^oC above the compensation temperature, a value of 20 oe for H, and we find that the minimum radius of a bit is about 6×10^{-3} centimeters. This conclusion is in excellent agreement with our experimental results.

It is clear from the above that domain walls must be eliminated to achieve a high packing density, and this has been done by separating the bits. Square segments have been made by scribing the GdIG wafer with a diamond stylus. The procedure for preparing samples is described in detail under heading 3.3. It has been found that switched regions are limited by the scribe lines if the cuts are deep enough. Figure 4-16 shows a small portion of a scribed GdIG platelet that has been switched. The size of the square is 25 microns.

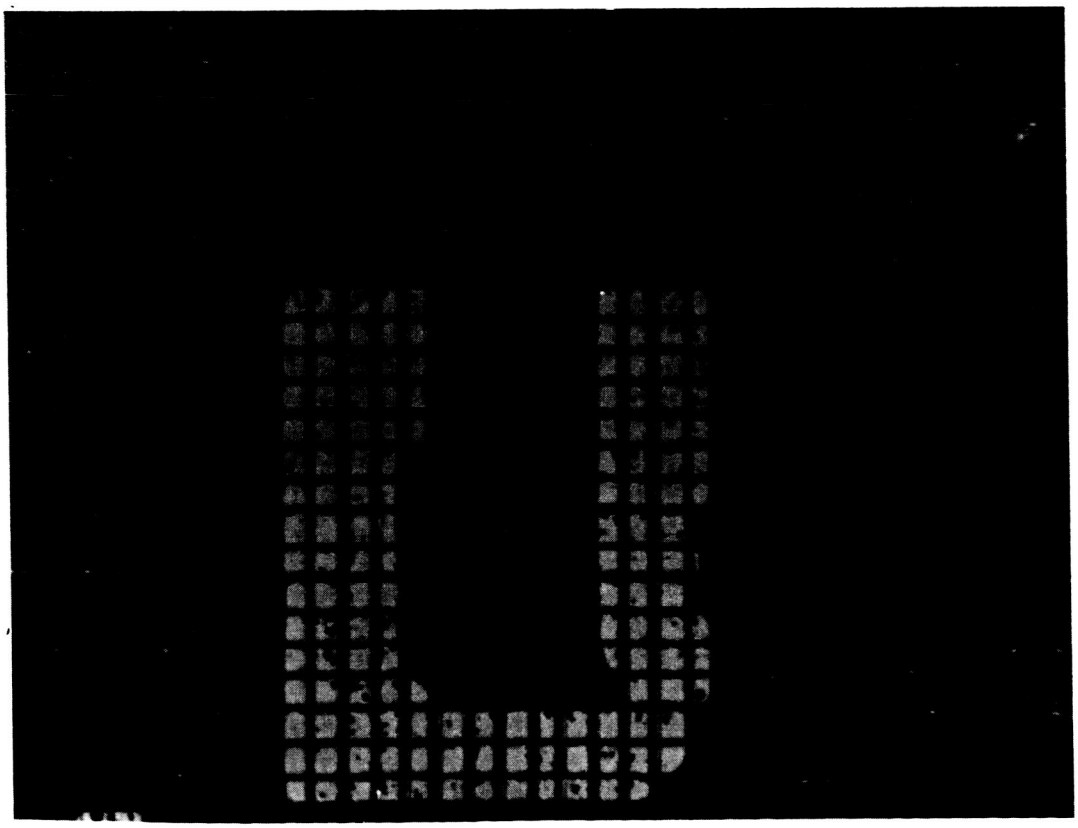


Figure 4-16. Portion of Scribed GdIG Platelet That Has Been Switched

SECTION 5

THEORETICAL

5.1. OPTIMUM THICKNESS AND WAVELENGTH

The optimum thickness of samples for observing changes in the Faraday rotation was determined as follows. The signal observed is

$$I = I_0 e^{-\alpha t} \sin^2(\beta t)$$

where α is the optical absorption constant, and β is the rotary power, and t is the thickness of the sample. We optimize this by setting the derivative with respect to t equal to zero

$$\frac{dI}{dt} = I_0 e^{-\alpha t} \left[-\alpha \sin^2(\beta t) + 2\beta \sin\beta t \cos\beta t\right] = 0$$

$$\alpha \sin\beta t = 2\beta \cos\beta t$$

for $\beta t \ll 1$

$$\tan\beta t \simeq \beta t \simeq \frac{2\beta}{\alpha}$$

$$t \simeq \frac{2}{\alpha}$$

Therefore the optimum thickness is one which reduces the intensity of the incident light by a factor of e^{-2}.

We now consider α and β as functions of the wavelength, and find the condition for maximizing the intensity with respect to variations of wavelength is

$$2 \frac{\frac{d\beta}{dx}}{\frac{d\alpha}{dx}} = \beta t$$

If we let the thickness have its optimum value, $\frac{2}{\alpha}$, the expression can be simplified to

$$\frac{d(\beta/\alpha)}{dx} = 0$$

This condition is equivalent to requiring that β/α be an extremum, and it is easy to show that it must be a maximum.

5.2. POWER REQUIREMENTS OF HEATING SOURCE FOR WRITING

For a flat plate with a high temperature in a region near $\rho = 0$ at time $t = 0$ such that $\int_0^\infty T(\rho)\, \rho d\rho = K$, the temperature at later times at a distance ρ from the initial high temperature point is given by[1]

$$T(\rho,t) = \frac{K}{2a^2 t} \exp - \frac{\rho^2}{4a^2 t}$$

where $a^2 = \frac{k}{dc}$. For garnets, the thermal conductivity, k, is approximately 1.5×10^{-2} cal/sec-cm-deg; the density, d, is 5.17 g/cm^3; and the specific heat, c, is 0.2 cal/g-deg. This yields a value of $a^2 = 1.4 \times 10^{-2}$ cm^2/sec. Note that the temperature T is the deviation from the intial temperature of the plate. For this value of a^2

$$T(\rho,t) = \frac{36K}{t} \exp - \frac{18\rho^2}{t}$$

---

[1] Margenau, H. and Murphy, G.M., The Mathematics of Physics and Chemistry, Vol. 1 (Princeton, N. J.: D. Van Nostrand and Co., Inc., 1943), p. 241.

The condition $\frac{dT}{dt} = 0$ determines the maximum temperature and yields the relation

$$t = 18\ \rho^2$$

Therefore, the maximum temperature at a distance of 10^{-3} centimeters from the laser beams occurs 18 microseconds after the laser pulse. Figure 5-1 is a plot of the temperature as a function of the distance from the heating beam. This is plotted for t = 9, 18, 36, and 54 microseconds.

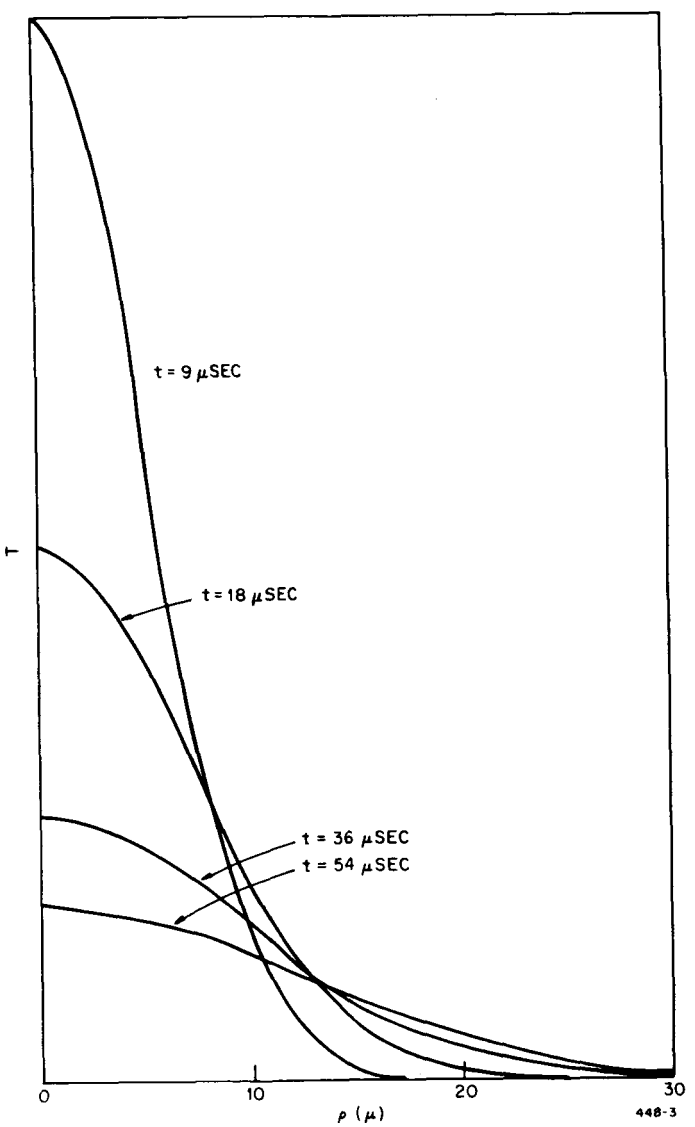


Figure 5-1. Temperature versus Distance for a Few Different Times

The above equation can also be applied to the more realistic case of a laser beam with a gaussian spatial intensity distribution. If the initial distribution is gaussian with the 1/e point at a radius of r, then the temperature at later times is

$$T = \frac{36K}{18r^2 + t} \exp\left[-\frac{18\rho^2}{18r^2 + t}\right]$$

The fastest and most efficient method of heating a region is to use a heating beam with a 1/e point approximately equal to the radius of the region to be heated. The power level must be high enough so that the heating time is small compared to the characteristic diffusion time, $18\ r^2$, where r is the radius of the region to be heated. The laser power required under these conditions can be estimated as follows:

The value of K was determined from the condition that $\int_0^\infty T(\rho)\rho d\rho = K$ to be $K = \frac{Pt}{2\ 4.186\ cdw}$ where P is the power absorbed, t is length of time it is absorbed, c, d, and w are the specific heat, the density, and the thickness of the platelet, respectively. For GdIG, $K = 3.7 \times \frac{10^{-2}Pt}{w}$.

The temperature at 1/e point is

$$T = \frac{36K}{18r^2} e^{-1} = 2.7 \times 10^{-2} \frac{P\tau}{r^2 w}$$

where P is the absorbed power, τ is the length of the laser pulse, w is the thickness of the sample, and r is the radius of the bit. A temperature change of $1^{\circ}C$ is adequate for writing purposes, and using this value and $r = 10^{-3}$ cm, $w = 10^{-3}$ cm and $\tau = 5$ microseconds, we find that P = 7 milliwatts. This is the absorbed power required to raise the average temperature $1^{\circ}C$. The temperature at the back side of the sample is approximately 1/5 of the average temperature, and therefore about 35 milliwatts are required to heat the entire region of interest at least $1^{\circ}C$. Of course there are losses in the deflection system, polarizers, etc. We therefore conclude that a 100 milliwatt laser is needed for the size bits that we have chosen.

It would be possible to decrease the time for heating by using a larger laser. However, such an increase would not have a significant affect on the random writing speed. The random writing speed will be determined by

the time required for sufficient heat to diffuse out of the region so that it cannot be switched by the next magnetic field pulse. An examination of Figure 5-1 shows that this time is approximately 36 microseconds for a bit with a radius of 10 microns. The only practical method of significantly increasing the random writing speed is by decreasing the radius of the bit. A decrease is difficult, but it offers a large bonus. An increase in the writing speed, a decrease in the laser power required, and an increase in packing density. The diffusion time can be slightly decreased by using a substrate with a large diffusion constant. Therefore, quartz substrates should be used to support the GdIG platelet.

When one is writing a large number of bits sequentially, the writing speed can be significantly increased by writing all the "zeros" at one time, waiting 35 microseconds, and then writing all the "ones". In this case the writing speed is essentially determined by the time to heat a bit and this could easily be reduced to a few microseconds.

SECTION 6

FEASIBILITY MODEL

6.1. GENERAL FEATURES OF MODEL

A system to demonstrate the feasability of the GdIG memory has been designed and built. Figure 6-1 is a simplified block diagram of the system.

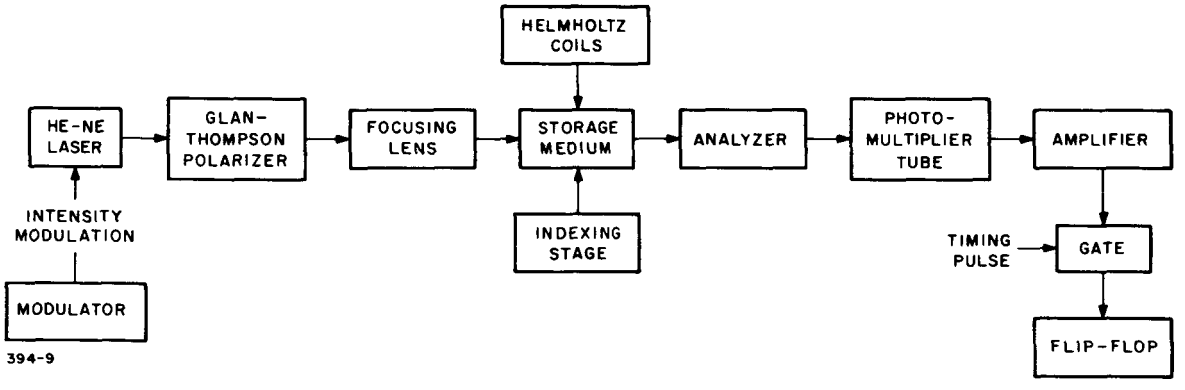


Figure 6-1. Block Diagram of System

The laser light source provides both the high power write (heat) pulse and the low power read pulse. These high and low power light pulses are obtained from the common laser source by intensity modulation of the beam. The laser beam passes through a Glan-Thompson polarizer and then through the sample. A pair of Hemholtz coils provide the means of applying the magnetic write pulse field which is applied coincident with the laser write (heat) pulse. The transmitted light beam emerging from the storage medium is then passed through a Glan-Thompson analyzer. The analyzer is positioned at an angle of 45 degrees with respect to the extinction angle. This positioning of the analyzer is desirable since this angle represents the position of maximum sensitivity. This positioning of the analyzer does present the

problem of a steady background illumination with changes occurring about this constant level. For proper operation of the AND gate it is necessary to provide a suitable bucking signal from the laser source and add it differentially to the background signal in a differential amplifier preceding the gate. The output signal from the amplifier is applied to one input of the AND gate and the signal to the remaining input is provided by a timing pulse. The simultaneous presence of a timing pulse and a high level output signal at the AND gate represents the storage of a 1, whereas the simultaneous presence of a timing pulse and a low level output signal represents the storage of a 0. The output of the AND gate is used to set a flip-flop.

The positioning of the storage medium will be accomplished by mechanically translating the crystal by a micropositioner which is driven with a slo-syn d.c. stepping motor. The d.c. stepping motor is capable of rotating in discrete steps of 1.8 degrees. Since one complete rotation of the micrometer head on the micropositioner represents a linear translation of 0.025 inch it is possible to move the stage in steps of 0.125 mil.

6.2. SELECTION OF MEMORY BIT

The laser beam is positioned at the desired storage bit by mechanical translation of the memory array crystal. The crystal in its mounting assembly is affixed to an x-y-z micropositioner. By adjusting the x and y controls of the positioner, the laser beam can be positioned to any desired location on the crystal. The z control facilitates focusing of the laser beam on the crystal. The positioner can be driven by a step servo motor in either the positive or negative directions in increment of 0.001", thus providing access to other storage bits at the chosen y value.

The laser beam is focused onto the memory storage plane through a 21 X Bausch and Lomb microscope objective. The light passing through the crystal is then collimated by another 21 x objective, directed through the analyzer onto the photocathode of an RCA C 70038D photomultiplier tube. The two 21 x microscope objectives are mounted on a screw lead controlled slides which facilitate the focusing of the laser beam. Figure 6-2 shows the mechanical arrangement of the lens, polarizer and analyzer, Helmholtz coils, memory plane crystal, step servo motor, and x-y-z positioner.

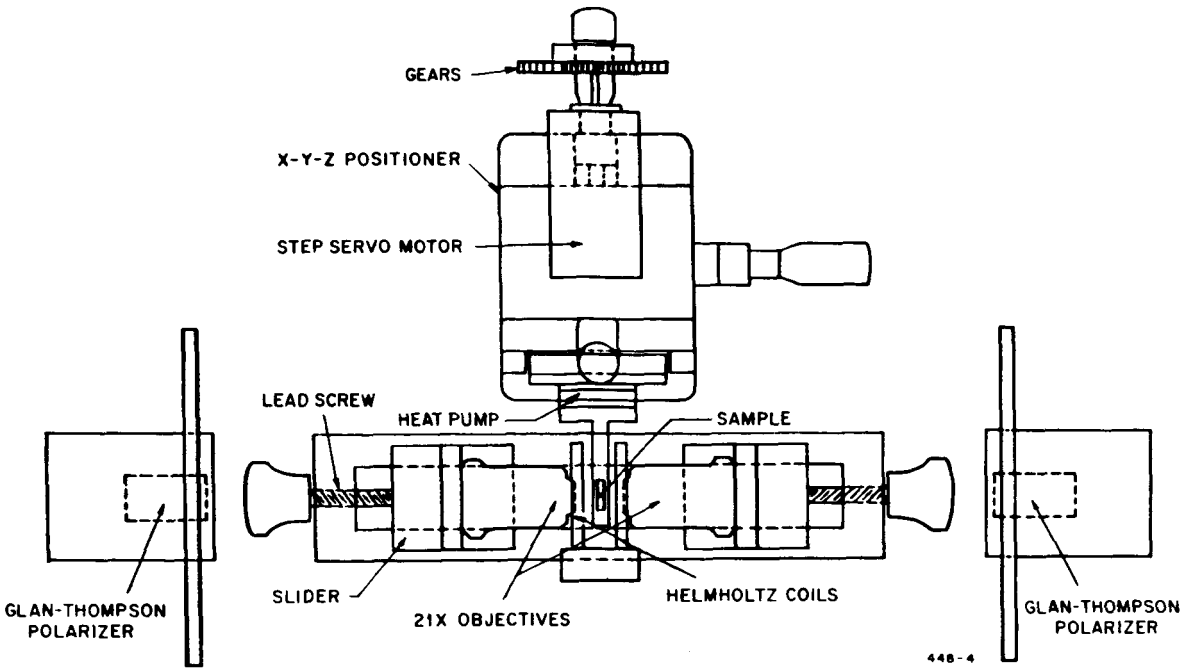


Figure 6-2. Top View, Mechanical and Optical Assembly

6.3. TEMPERATURE CONTROL OF MEMORY ELEMENT

The GdIG platelet must be kept at the compensation temperature during memeory operation. We have designed and built equipment to do this. The heart of the equipment is a bismuth-telluride thermoelectric heat pump. It can heat or cool the sample depending on the direction of the current through it. The current supplied to the device is an inverse function of the deviation of the temperature from the compensation temperature. Thus overshooting and hunting is avoided.

A schematic diagram of the temperature control unit is shown in Figure 6-3. The values of R_1 and R_2 are chosen so that the thermister, which is in thermal contact with the sample, is kept at the compensation temperature at the quiescent level of the feedback system. The thermister's resistance depends on the temperature. At temperatures above the compensation point, the R_1, R_2, and thermister combination supplies sufficient current to Q., to overdrive the amplifier (Q_1, Q_2, Q_3). This overdrive saturates Q_4 and Q_5 and the heat pump receives approximately 2 amperes of current. As the sample is cooled, the internal resistance of the thermister increases thereby decreasing the driving current. The process continues until the quiescent current level is reached at which level the thermister is maintained at the

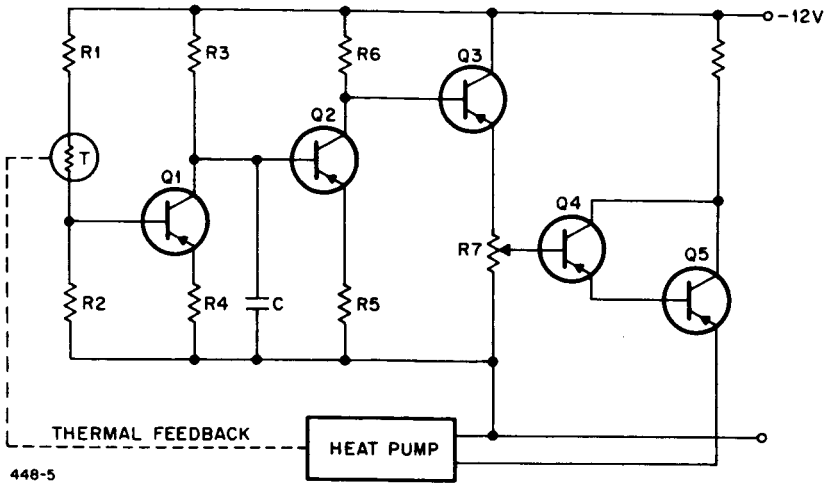


Figure 6-3. Temperature Control Unit

compensations temperature. The temperature of the sample can be controlled to $0.05^{o}C$ with our setup.

In the testing procedure the output signal from the photomultiplier is amplified and applied to one input of an AND gate; the other input to the AND gate is the read interrogate pulse. The simultaneous occurrence of a high signal from the amplifier (stored "1") and the read interrogate pulse at the AND gate will generate a set pulse at the flip-flop which in turn will drive an indicator. The occurrence of a low signal from the amplifier (stored "0") at the gate in conjunction with the read interrogate pulse will not set the flip-flop.

The memory program consists of writing a "1" and then performing n read operations, followed by the writing of an "0" and an additional n read operation. The memory plane can then be indexed to the next memory position and the program repeated.

6.4. AMPLITUDE MODULATION OF THE LASER BEAM

Two methods of modulating the laser beam have been investigated: internally at the RF exciter or by an external retardation cell Model 320 made by Spectro Physics, Mountain View, California. External modulation was chosen because internal modulation was noisier. The electronics necessary to operate the modulator have been designed and built and the schematic diagrams of the circuitry is shown in Figure 6-4. The circuits previously re-

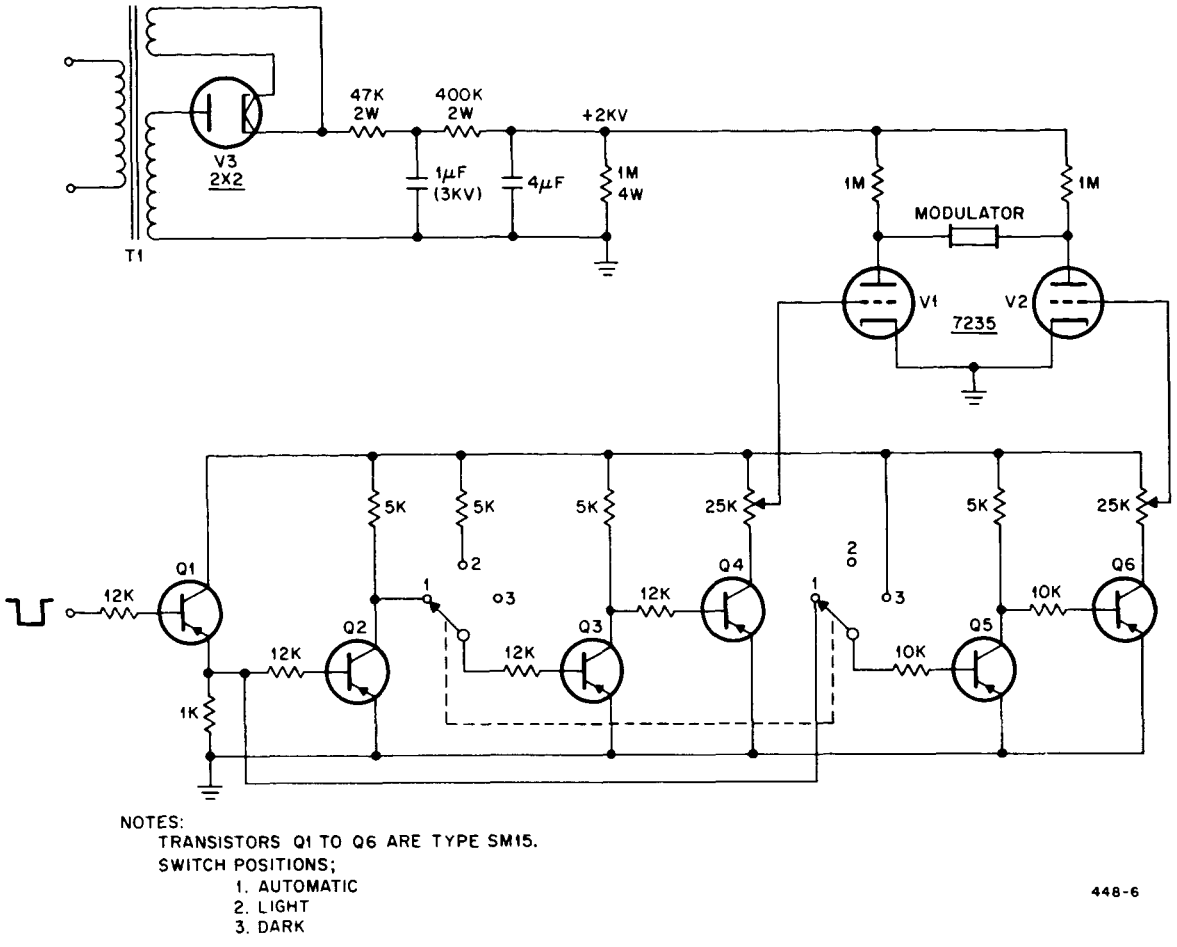


Figure 6-4. Drive Circuitry for the Modulator

ported in Monthly Letter Report No. 11 were not satisfactory. The equipment will operate at rates up to 100 KHz with up to 80 percent modulation.

The Model 320 Modulator has as its essential component a voltage variable retardation cell based on the Pockel's effect, which is capable of rotating the plane of polarization of linearly polarized light. The cell is combined with a quarter wave plate and a polarizing prism. When there is no voltage applied across the retardation cell (KDP), the crystal is optically uniaxial, and the plane of polarization of the light is not affected. When a voltage is applied, the crystal becomes biaxial, and the plane of polarization is rotated.

The quarter wave plate and polarizing prism are keyed to proper orientation with the retardation cell. When no voltage is applied, the optical power is one half the input power. When the positive voltage which rotates the plane 45^{0} ($V_{\lambda/4}$) is applied the power output is maximum. When $-V_{\lambda/4}$ is

applied, the output is minimum. This is shown in Figure 6-5. We have found that $V_{\lambda/4}$ is about 800 volts.

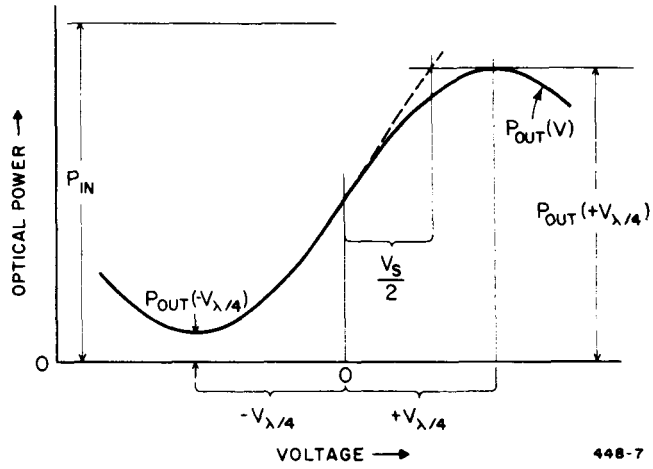


Figure 6-5. Power Output of Modulator as a Function of Voltage

6.5. TESTING PROCEDURE

A detailed block diagram of the testing system is shown in Figure 6-6. The timing diagram for the demonstration system is shown in Figure 6-7. The laser power for reading, P_r, and writing, P_w, the length of the laser write pulse, and the amplitude and length of the magnetic pulse are adjustable. The clock rate of the system is variable in four steps: 500 Hz, 1 KHz, 5 KHz, and 10 KHz. Schematic diagrams of the clock and associated circuitry have been included in Monthly Letter Report No. 11 and are not repeated here. Also included in that report is schematic diagram of the Helmoltz coil drive circuitry, and a description of the coil

6.6. RESULTS OF TEST PROGRAMS

The results of the test program have demonstrated the general feasibility of a GdIG memory. It has also uncovered a number of problems which still require solution.

We have found that one can write into the sample by heating it with a laser beam and simultaneously applying a field. With the 10 milliwatt laser, and 25 oe field, the minimum time for writing on a platelet about 50 microns thick was 1 millisecond. This result is consistent with our calculation

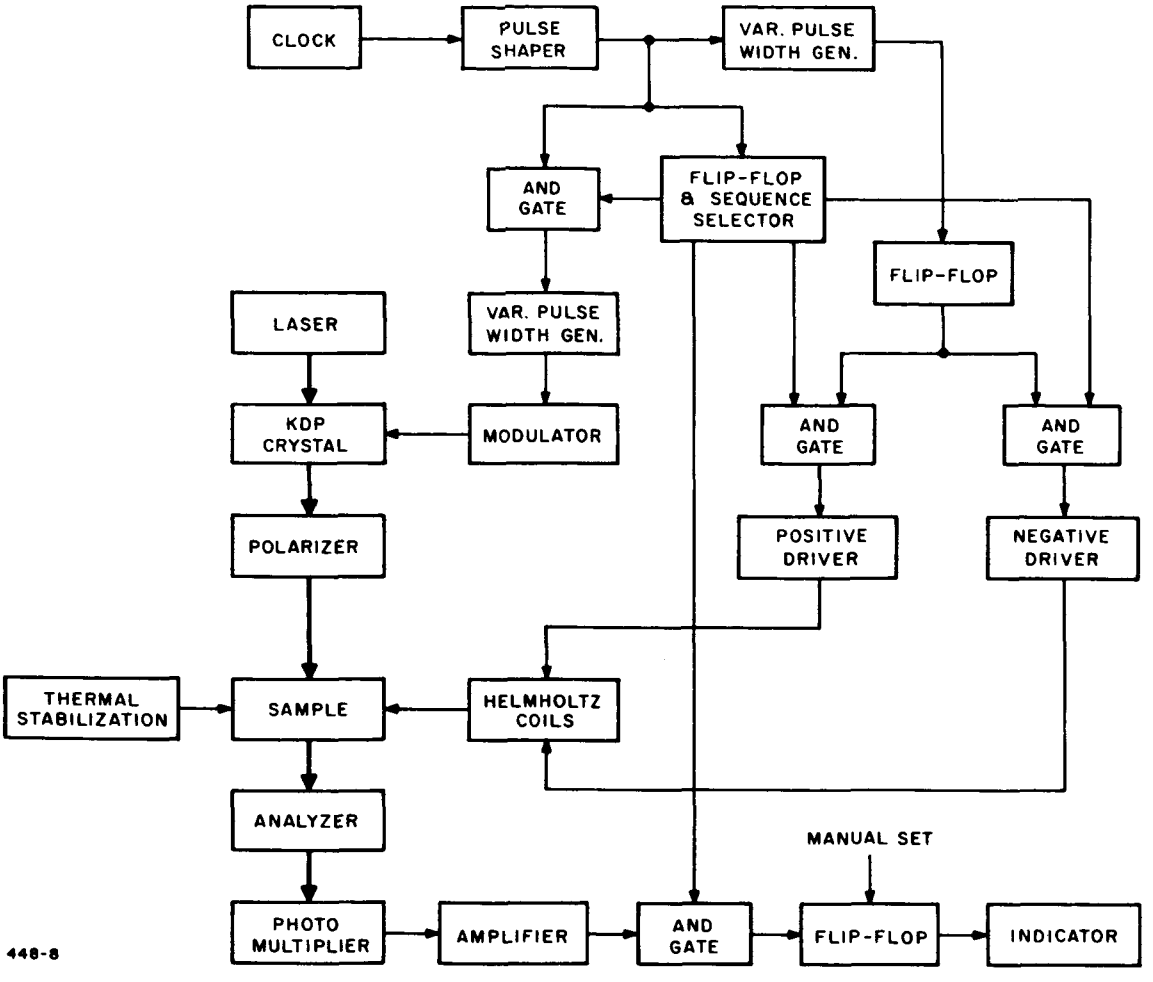


Figure 6-6. Block Diagram of Testing System

(heading 4.3) of heating time. We have not determined the ultimate speed of the reading operation, but it certainly exceeds 1 MHz. The difference in signal from the photomultiplier for a "0" and "1" was 1/2 volt with a signal-to-noise ratio greater than 10.

We have used a thicker platelet than the ideal value because larger rotations were required. This need for larger rotations arose because of the presence of the scribe lines. Light passes through the scribe lines and caused a high background level, which in turn necessitated the larger Faraday rotation signals. The extra thickness of the sample introduced other problems. The scribe lines did not cut completely through the samples, and therefore the bits were not limited to one square. We found that typically three or four bits were switched at one time with the thicker samples.

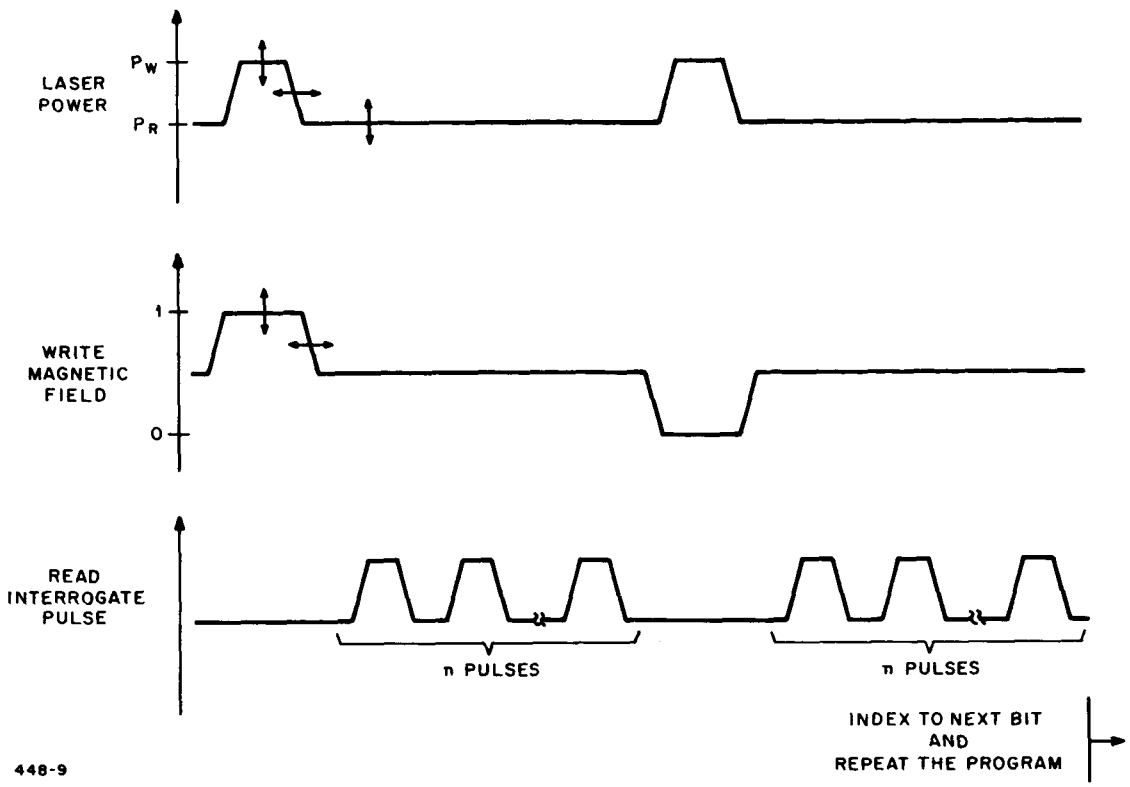


Figure 6-7. Timing Diagram

We have not solved this problem at this time. But the method of solution is clear and realizable. The light which passes through the scribe lines must be eliminated. This can be done by either focusing the laser beam to a small diameter or by making the cracks opaque. A beam expander can decrease the size of the focused beam significantly. The scribe marks can be made opaque by filling them with an inky fluid. Efforts to do this have been initiated.

If the light from scribes is eliminated, thinner samples will provide adequate signals and it will be possible to scribe completely through the sample. Also, operation with an argon ion laser will result in larger signals and thereby ease all these problems.