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Final Technical Report
March 1975

INVESTIGATION OF SEMICONDUCTOR LASERS FOR WIDEBAND RECORDING

Radio Corporation of America

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Rome Air Development Center
Air Force Systems Command
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The purpose of this investigation was to determine if it is feasible to build a wideband laser recorder using a semiconductor laser as the film exposure source. The argon laser and its external light modulator of a Government furnished, developmental wideband FM recorder/readout system were replaced by an internally modulated laser diode. The lasers were developmental (Al Ga)As devices supplied by RCA Laboratories. These double-heterojunction lasers were capable of emitting continuous output powers up to 10 mW at 710 nm when operated at 77°K.

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Modulation and recording tests have shown that a laser diode can provide equivalent or superior performance compared to that of an argon laser. The semiconductor lasers have been internally modulated from 1-200 MHz (± 2dB) and film recording frequencies in excess of 100 MHz (160 cycles/mm) have been made. Stationary film playback of a 30-MHz FM recording achieved a 31 dB (p-p to rms) wideband signal-to-noise ratio over a 30-MHz bandwidth.

Tradeoffs for diode operation at elevated temperatures are discussed. Comparisons are made between semiconductor laser performance and data taken previously on the argon laser recorder.

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EVALUATION

Laser recording systems are typically large, complex and consume relatively large amounts of power. Consequently, they are expensive to purchase as well as maintain. Primary contributors are the gas laser, light modulator and mechanical spinner. Semiconductor laser diodes offer an excellent means of reducing size, complexity, power consumption and ultimately the cost of such systems.

To date, the inability to construct truly coherently radiating diodes at usable wavelengths has been the major stumbling block. The result of this effort has been to show that semiconductor laser diodes could be constructed with operating wavelengths compatible with available films, that could be internally modulated, with lifetime and cost commensurate with gas laser externally modulated systems.

Reported are the results of a study effort utilizing a GFE wideband laser recorder where a gas laser and external light modulator were replaced with a laser diode and cooling structure. The diodes had an output wavelength of 720 nm at an operating temperature of 77°K and were used to achieve film recordings in excess of 100 MHz with a SNR in excess of 30dB. In addition, FM recordings over a 30 MHz bandwidth yielded a signal to noise ratio of 31dB. The laser diode recorder showed impressive improvements in several equipment and recording parameters such as power consumption, required light power, contrast ratio, spot power available, optical losses and beam geometry. Coupled with significant decreases in size and complexity, internally modulated semiconductor laser diodes represent an extremely viable alternative to externally modulated gas lasers for wideband recording applications.

More recent developments in the area include room temperature laser diodes that lase in the area of 800 to 820 nm. However, at present, these are limited by a lack of film with suitable granularity for wideband recording applications.

Jack D. Petruzelli

JACK D. PETRUZELLI
Project Engineer

SECTION I

INTRODUCTION

A. BASIS FOR THE INVESTIGATION

The objective of this project was to investigate the feasibility of using a semiconductor laser diode as the exposure energy source in a wideband film recorder. Laser recording systems presently use gas lasers, external laser beam intensity modulators, and high speed rotating mirror assemblies. While impressive performance has been achieved, these systems are typically bulky, mechanically elaborate, and expensive. If laser recording is to be used for other than a few highly specialized data capture applications, the component costs must be reduced, and the reliance upon high precision mechanical parts must be minimized. A step in this direction is to replace the gas laser and external light modulator with an internally modulated, semiconductor laser to generate the record signal. Laser diodes are attractive record signal sources since they are compact, they can be internally modulated at very high rates, and they are potentially inexpensive. These lasers are small, rugged, and reliable and require only a few watts at a few volts for operation.

Two developments have made the use of laser diodes in wideband recording systems worth considering at this time. First, laser diodes that emit continuously at wavelengths below 720 nm and at power levels suitable for wideband film recording have recently been fabricated.[1] Secondly, extended red-sensitive holographic films have been developed by Kodak and Agfa-Gevaert that may be used at wavelengths above 700 nm. These films have become commercially available and are being used in developmental laser recorders. In addition, 3M has developed an experimental dry silver film that is sensitive to 700 nm.

The principal goals of this investigation were to achieve wideband internal modulation and detection of the output of developmental CW injection lasers, to record signals up to 100 MHz on film, and to evaluate the film recordings. The bulk of the experimental work was conducted at a diode operating temperature of $77^{o}K$. The effect on diode operation of higher temperatures where thermoelectric cooling could be used was also considered.

B. METHOD OF INVESTIGATION

A dewar was built to test the diodes and the performance of several diodes was evaluated. The recorder was modified to accept a laser diode source. Recording and playback tests were conducted.

1. Fabrication of Diode Cooling and Mounting Structure.

One of the first tasks in this program was to determine the diode geometry and other characteristics that would give the best performance in a laser recorder. A cooling and mounting structure was designed which would allow the diodes to be conveniently tested at various temperatures by the introduction of a suitable coolant. The dewar was designed to minimize optical alignment and wavefront distortion problems, to provide good thermal contact with the diode, and to allow wideband modulation at frequencies in excess of 250 MHz. For details see Section II-B, C.

2. Evaluation of Diode Samples.

Three sets of diode samples were supplied by RCA Laboratories. Although the third set proved to be the best suited to film recording, all three sets (12 diodes) were extensively tested. The diode characteristics to be determined were the geometry of the lasing region, output power, operating temperature, beam divergence, mode beat noise, modulating frequency response, and polarization. The tests determined that stripe geometry double-heterojunction diodes could be fabricated with sufficient output power at the required output wavelength of less than 720 nm, if the diode is cooled to the 77^{o}K range. Small changes in junction temperature cause the lasing threshold to increase, drastically reducing laser power. At 77^{o}K, the characteristics of these diodes proved excellent for film recordings.

Wideband modulation tests were conducted; the beam divergence and intensity distribution and recording spot profiles were measured. The data gathered was used to design the optical system needed to integrate the laser diode with the existing recorder test bed. Test data is contained in Section II-D and Section IV-C.

3. Modification of the Existing Developmental Laser Recorder.

The argon laser and light modulator were replaced by the laser diode source. These two components along with a beam expander were bypassed and additional optics was installed to collimate the laser diode beam and direct it into the imaging lens of the recorder (See Figs. 31 and 36). An optical bench was installed to support the additional components. A special mount was designed to orient the diode with the optical axis of the system. Details are contained in Section IV.

4. Film Recording Tests.

After the optical/mechanical interface with the recorder was completed, recording tests were conducted. Both single tone and FM recordings were made. The majority of the record tests were conducted at a spot velocity of 63,500 cm/sec (25,000 in/sec) using one or both of the two hexagon mirrors within the film scanner. Record/playback tests of FM recordings at 5 and 30 MHz were conducted at a spot velocity of 92,000 cm/sec (36,000 in/sec) using a single hexagon mirror. See Section IV.

C. RESULTS AND CONCLUSIONS

Semiconductor lasers have demonstrated excellent performance when used in the wideband laser recorder to replace the argon laser and its external modulator. The lasers are double heterojunction, (Al Ga) As devices emitting up to 10 mW at 710 nm when operated at 77°K. The output power and beam intensity distribution were sufficient to allow continuous recording at 63,500 cm/s (25,000 in/s). These injection lasers have been internally modulated from 1-200 MHz (± 2dB) and film recordings of signal frequencies in excess of 100 MHz (160 cycles/mm) have been made. FM record/playback tests were conducted in a stationary-film mode and a wideband signal-to noise-ratio of 31 dB (p-p to rms) over a 30-MHz bandwidth was attained. In many respects the performance of the laser diodes appeared superior to that obtained with the externally modulated argon laser. Semiconductor lasers offer significant improvements in ruggedness, stability, weight, size, and power consumption over conventional laser techniques.

CW semiconductor lasers have recently been developed that are capable of 5 to 10 mW at 800 nm and more than 30 mW at 820 nm at room temperature. Fine grain infrared film (Kodak SO-289) is compatible with these wavelengths and has the resolution required for a high quality image recorder. Recently developed, high efficiency, acousto-optic deflectors could replace the scanning mirror, allowing the construction of an all solid state laser recorder. Such a solid state recorder could provide signal recordings suitable for optical processing and could also be capable of recording TV-rate imagery directly onto film.

SECTION II

THE LASER DIODE AS A FILM EXPOSURF ENERGY SOURCE

A. FUNDAMENTALS OF OPERATION AND AVAILABLE DIODE GEOMETRIES

The key characteristics of a laser diode to be used as a record signal source are the lasing threshold current density, external quantum efficiency, emission wavelength and intensity, emission pattern, and the rate at which it can be modulated.

A laser diode is a p-n semiconductor junction with opposite ends cleaved to form an optical cavity. Recombination of excited electrons with holes in the vicinity of the junction (active or recombination region) produces light. An excess of excited electrons, which leads to laser action, is achieved by applying a forward bias to the junction and by tailoring the construction of the diode. Above a given current density (threshold current), a guided light wave is generated in the plane of the junction. This wave propagates in a direction perpendicular to the cleaved reflecting faces. The threshold current can be reduced by reducing the volume of the recombination region, thereby improving performance in many applications.

Four basic structures of laser diodes are shown in Fig. 1 along with the features of each design. For the sake of clarity, the devices shown have an active region of GaAs material which results in emission wavelength of about 900 nm. The homojunction was an early developmental model with a high lasing threshold current density (50,000 A/cm^2 at 300^oK) which made CW operation impractical. In an effort to reduce the drive and thermal problems by reducing the threshold current, the single heterojunction was conceived. A heterojunction is a junction between dissimilar materials, in this case GaAs and (AlGa)As. The recombination region (d) is reduced to about 2 μm, reducing the threshold to 8000 A/cm^2. The heterojunction serves to confine the electron-hole carriers between the heterojunction and the p-n junction. Since the index of refraction of (AlGa)As is different from GaAs, the radiation is also better confined, increasing the laser action.

The double hetrojunction uses a heterojunction on each side of the p-n junction, improving carrier and radiation confinement and reducing the lasing threshold current density (2000 A/cm^2). The recombination region and optical cavity overlap, as in the previous devices, and the width of d is about 1/2 μm. The disadvantage of this structure is that high peak pulse powers cause internal damage. However, moderate output powers can be continuously maintained.

To overcome the catastrophic internal damage caused by high radiation densities, the large optical cavity (LOC) was designed. This device keeps recombination region d_2 small, as in the double heterojunction, but increases the optical cavity ($d_2 + d_3$) up to 10 μm. The (AlGa)As-GaAs junctions exhibit a large change in index of refraction and, therefore, define the optical cavity. The recombination region is determined by doping in the GaAs. The LOC device reduces the optical damage for high peak output

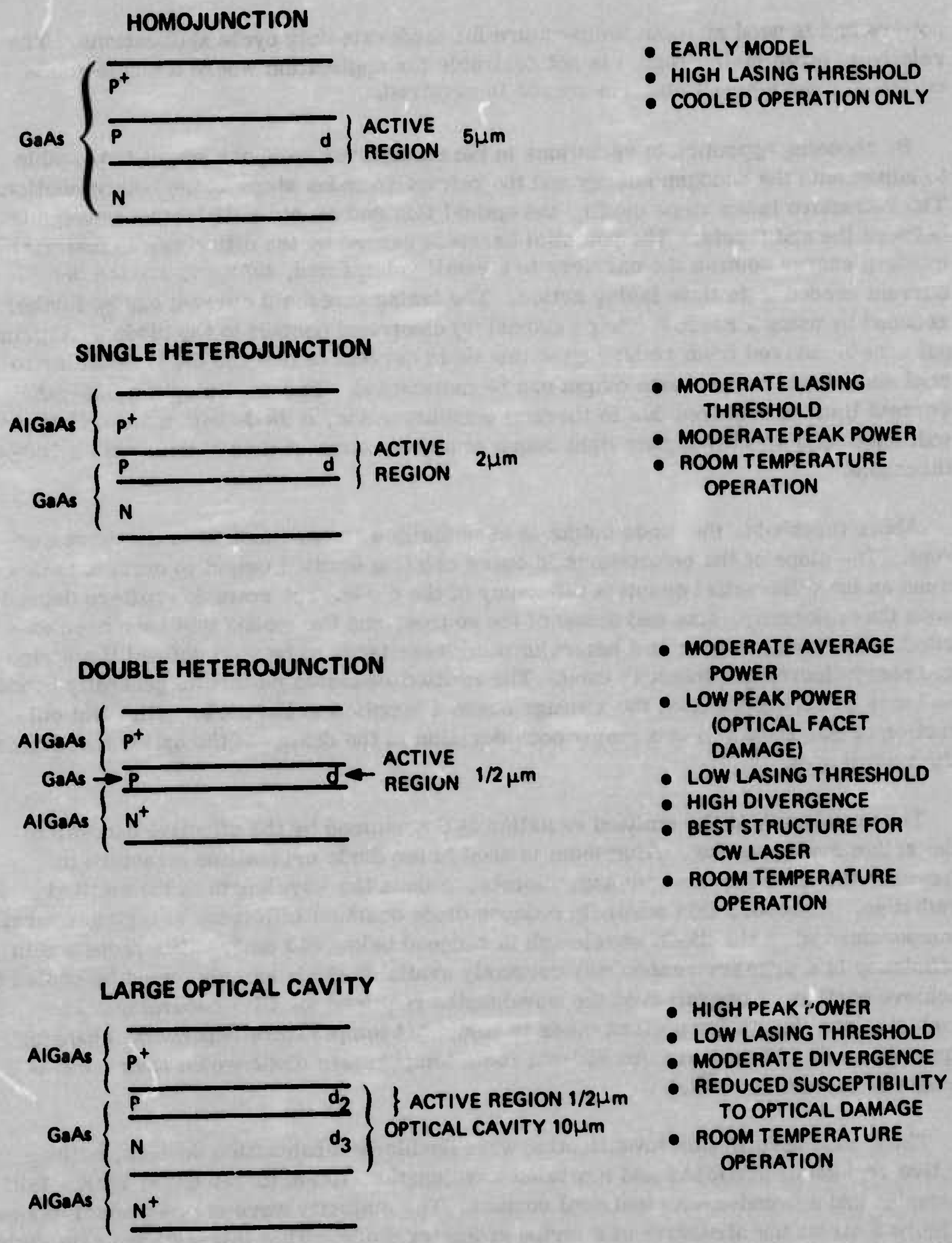


Fig. 1. Laser diode structures

powers and is used at room temperature for moderate duty cycle applications. The relatively large lasing region is not desirable for application where a single-mode emission from a small uniform source is required.

By choosing appropriate variations in the diode layer composition, it is possible to adjust both the bandgap energy and the refractive index steps at the heterojunctions. The refractive index steps confine the optical flux and create a dielectric waveguide between the end facets. The potential barriers caused by the difference in material bandgap energy confine the carriers to a small volume and, thereby, reduce the current needed to initiate lasing action. The lasing threshold current can be further reduced by using a narrow (stripe geometry) electrical contact to the diode[2]. A principal benefit derived from reducing the threshold current is that the diode is easier to cool and a higher continuous output can be maintained. For example, if a 500-mA current limit is required due to thermal considerations, a diode with a 350-mA threshold will have considerably higher light output at a given current than a diode with a 100-mA threshold.

Above threshold, the diode output is essentially a linear function of the drive current. The slope of the characteristic curve relating emitted output to current is defined as the differential quantum efficiency of the diode. The emission pattern depends upon the uniformity, size and shape of the source, and the modes that have been excited. The lasing region of a heterojunction laser tends to be well defined if a stripe geometry electrical contact is used. The emitted radiation pattern is generally broad and may be dependent upon the average current supplied to the diode. Efficient collection of this radiation is a major consideration in the design of the optics that forms the record spot.

The wavelength of the emitted radiation is determined by the effective bandgap of the active diode junction. Aluminum is used in the diode crystalline structure to increase the effective bandgap and, thereby, reduce the wavelength of the emitted radiation. However, this severely reduces diode quantum efficiency at a given operating temperature when the diode wavelength is reduced below 800 nm[3]. This reduction in efficiency is a primary reason why currently available diode samples must be cooled to achieve continuous operation at the wavelengths required for film recording. The emission wavelength for a given diode is somewhat temperature dependent, changing approximately .15 nm/$^{\circ}$K. An 800-nm room temperature diode would have a wavelength of 750 nm at 77°K.

The diodes used in this investigation were double-heterojunction devices, with active regions of (AlGa)As and emission wavelengths 710 nm to 750 nm at 77°K. Initial samples had a broad-area electrical contact. The majority were stripe contact devices. Figure 2 shows the structure of a stripe geometry diode. This investigation established that CW, double-heterojunction, stripe contact lasers emitting at wavelengths of 720 nm or less are preferred for use in wideband analog signal recorders.

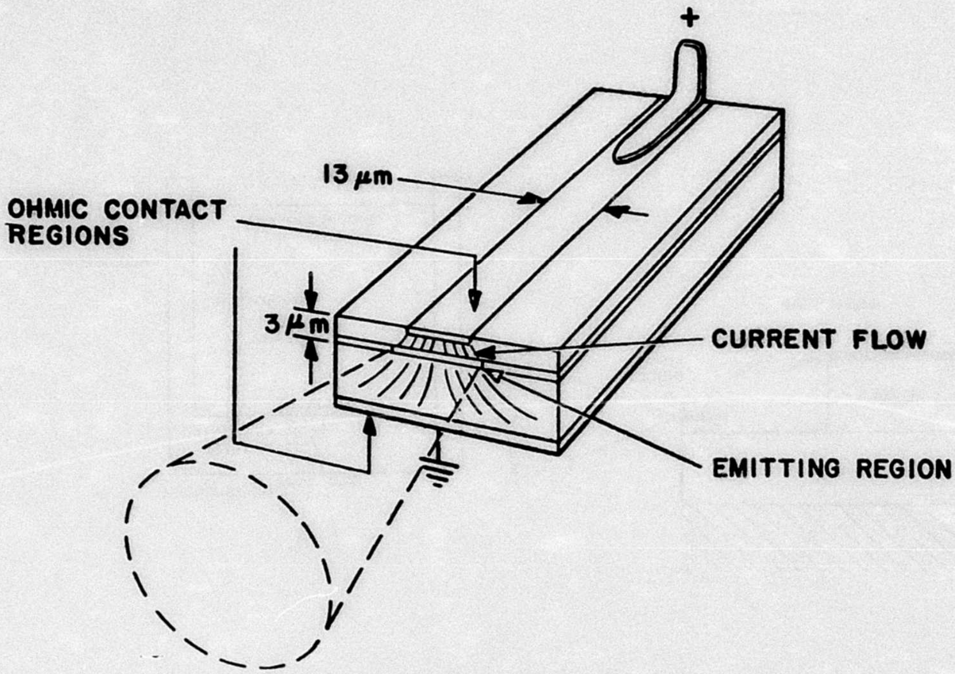


Fig. 2. Double-heterojunction stripe contact laser diode.

B. DIODE COOLING AND MOUNTING STRUCTURE

To provide sufficient light at wavelengths compatible with high resolution films, the laser diodes were cooled. Although mechanical cryogenic refrigerators are commercially available, increased experimental flexibility is afforded by using cryogenic fluids in the custom cooling and mounting structure shown in Fig. 3. The dewar is shown in Fig. 4, and the diode mounting on the dewar is shown in Fig. 5. This unit, which is approximately 10-inches high and 7-inches in diameter, is constructed primarily of stainless steel. The laser diode is mounted on and cooled by conduction through a copper plug. Tests at temperatures above liquid nitrogen can be conducted by using a suitable liquid coolant. The diode is placed in a vaccum to prevent frost formation on the emitting facet. The cooling and mounting structure has been designed so that the diode output intensity can be modulated at frequencies in excess of 250 MHz.

C. ELECTRICAL DRIVE REQUIREMENTS AND WIDEBAND INTERFACE

For an analog signal recorder, it is desirable to bias the laser diode well into the lasing region with a dc current and then modulate the laser light by applying an ac signal current. The optimum dc and ac current will vary from diode to diode. The dc current must be sufficiently above threshold to avoid signal distortion by the toe of the characteristic curve. The ac current swing must be sufficient to produce the desired contrast ratio (10:1) for film recording without introducing excessive harmonic distortion by exceeding the linear range of the diode characteristic curve.

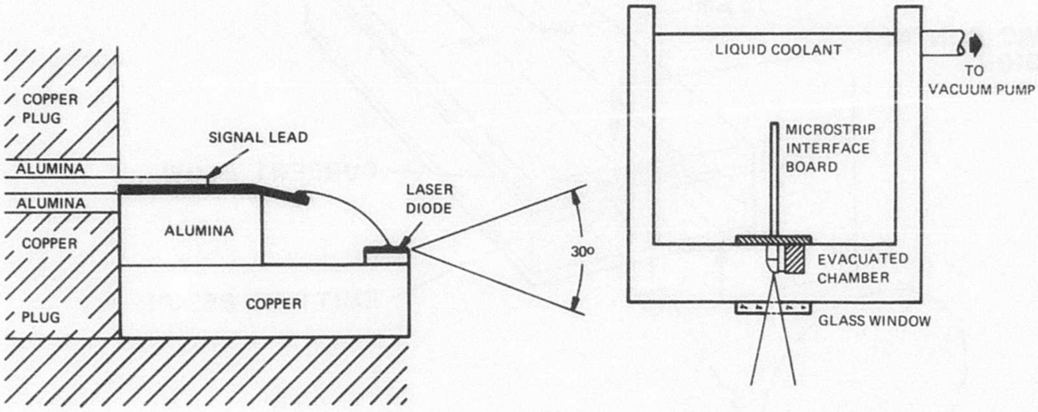


Fig. 3. Cooling and mounting structure.

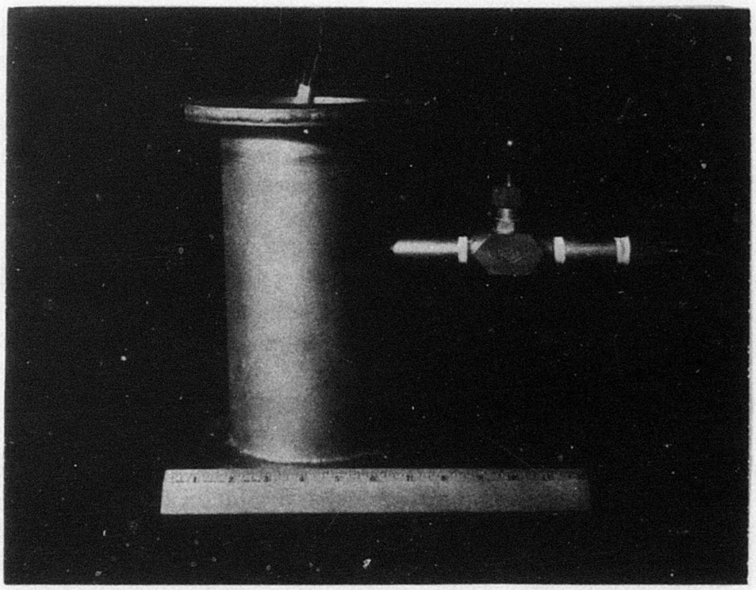


Fig. 4. Dewar.

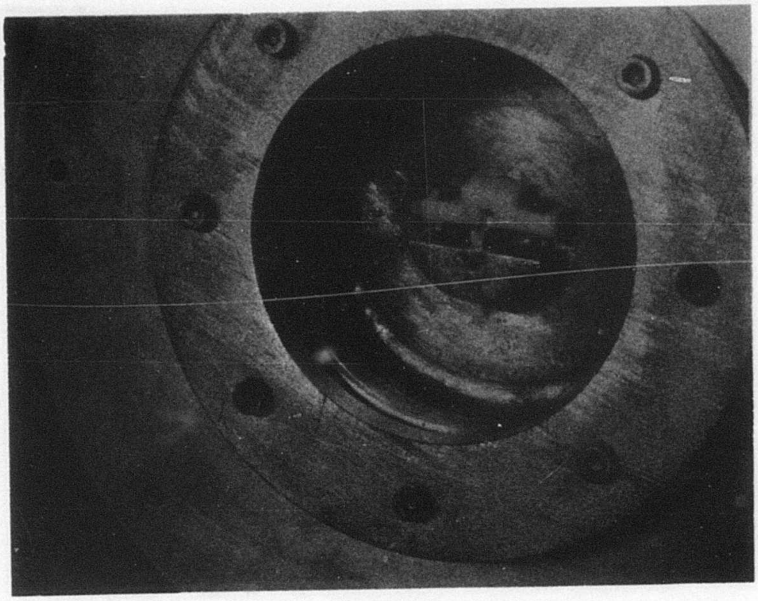


Fig. 5. Diode mounted in dewar.

The electrical power input P_I to the laser diode is the sum of the junction power and the Joule heating in the dynamic series resistance R of the diode:

$$P_I = I_D E_g + I_D^2 R$$

where

I_D = drive current

E_g = bandgap energy (1.65 to 1.8 eV)

R = series resistance (1/10 to 1 Ω)

To achieve wideband operation, the record signal is applied to the diode through a hybrid interface network that is placed close to the diode in the cooling and mounting structure. Figure 6 shows a schematic of the drive system.

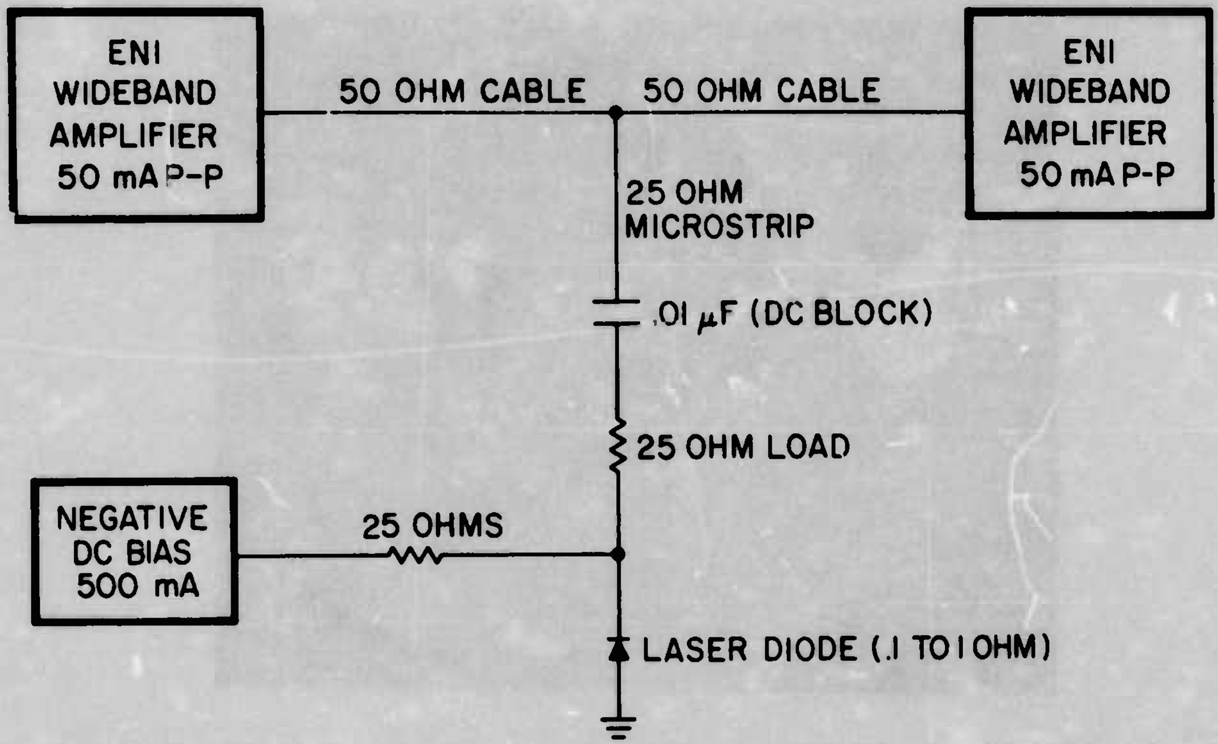


Fig. 6. Drive interface schematic.

Wideband ac modulation is supplied by a phase-matched pair of wideband drivers. Each driver (ENI Model 406L) is capable of delivering 5 W into 50 ohms over the frequency range extending from 150 kHz to 250 MHz. A load resistor is placed in series with the diode and connected to the drivers by parallel 50-ohm lines. The 25-ohm load resistor must be placed as close as possible to the diode to minimize reflection. The bias current is brought through a 25-ohm resistor to the diode. To prevent either resistor from heating the diode, the interface board was placed in the liquid coolant. For the 500-mA bias and 100-mA peak-to-peak signal current used in initial recordings, the interface network dissipates 6 W. The ac signal power requirement is well within the capability of a single driver. Two drivers were used to provide additional capability if needed and to allow operation at moderate drive levels to minimize distortion.

The heat input to the dewar from room temperature surroundings has been calculated to be 8 W, just slightly higher than the electrical heating. Tests have shown that 2 to 3 quarts of liquid nitrogen coolant are required for 8 hours of operation with the operating parameters specified above.

D. OPTICAL PARAMETERS

1. Beam Patterns, Track Widths

An important consideration with laser diodes is the efficient collection of the highly divergent output beam. The beam patterns of the diode used for recording (709.5 nm, stripe contact) will be used to illustrate the problem. The diode beam divergence is markedly different along 2 axes, - perpendicular to the plane of the junction and parallel to the plane of the junction, as shown in Fig. 7. The beam perpendicular to junction plane, used for the along-track direction of the record spot, measures 32° full angle to the half intensity points. The beam parallel to the junction plane varies from 5° to 15° (full angle to null) with drive current. Non-uniformities in beam intensity in the parallel direction are caused by exciting higher order modes in this direction at drive currents significantly above threshold. The narrow dimension of the diode junction (junction width) produces a highly divergent single mode beam. The junction length, the longer dimension of the diode junction when viewed from the end facet produces a multimode beam of moderate divergences. This inverse relation is predicted by diffraction theory for a rectangular aperture (excluding multimode effects) as:

$$\tan \theta = \frac{\lambda}{D}$$

where:

θ = half angle of beam

λ = wavelength

D = aperture size

Figure 8 shows the beam patterns of the selected diode at 3 current levels at a distance 2 inches from the diode. The effect of multimoding on the beam pattern at higher drive current levels is apparent. When imaged through the recorder optical system, the variation of the across-track beam divergence with current results in a variation of spot size in the track-width direction with current as shown in Fig. 9. The spot photographs were obtained using the f/2, 100-mm collection lens and f/2.8, 150-mm spot focusing lens of the recorder optics described in Section III. A 2.5-cm x 1-cm

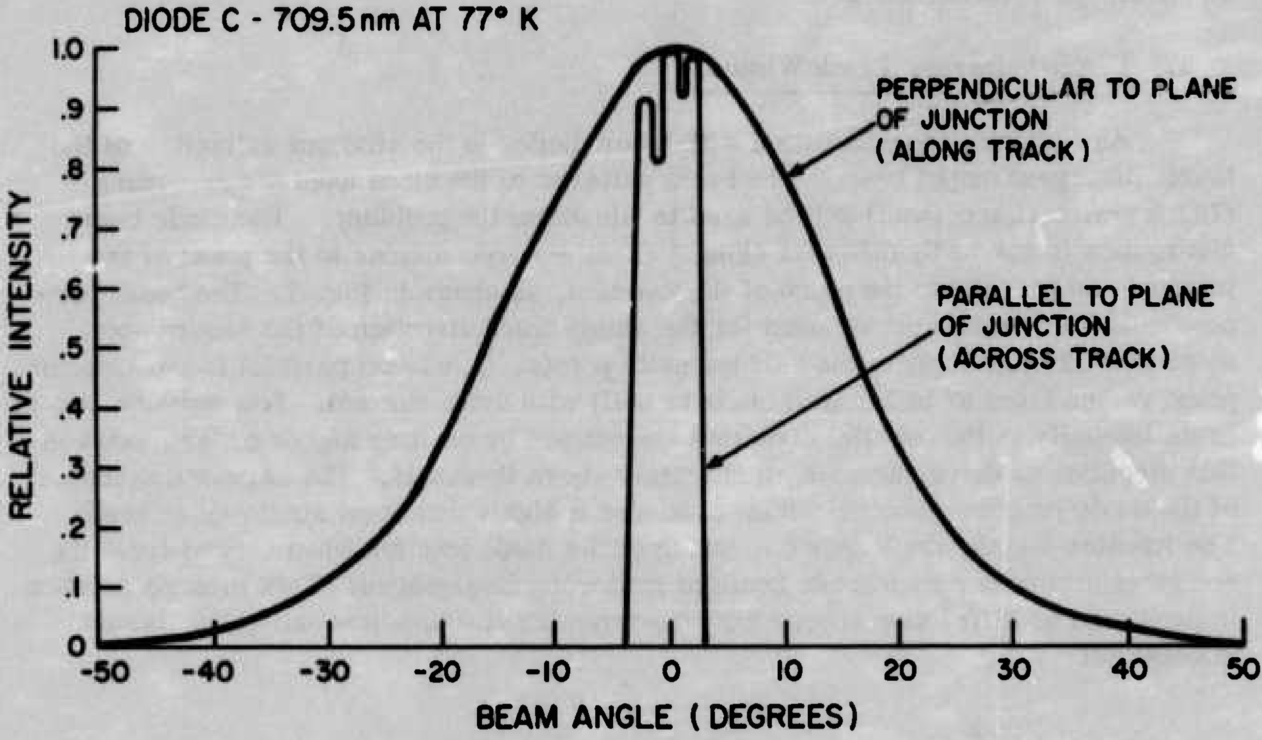
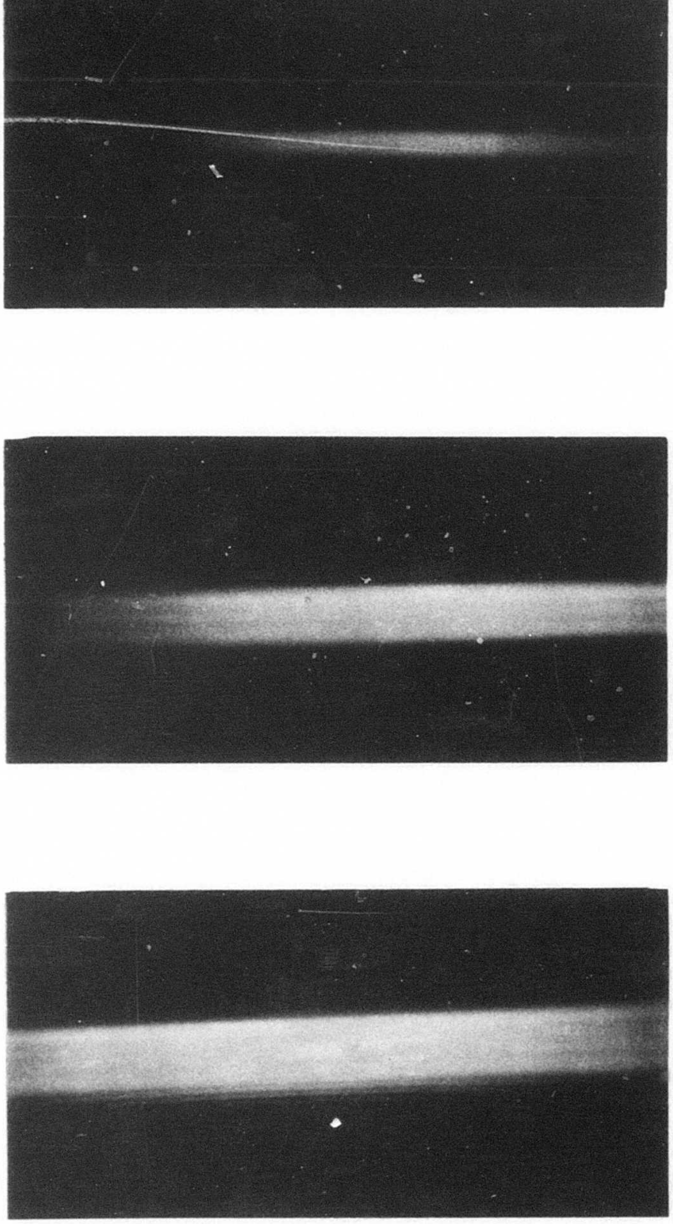


Fig. 7. Beam profile at 495mA.

aperture was placed before the spot forming lens to simulate one facet of the scanning mirror as shown in Fig. 10. The data of Figs. 8 and 9 can be summarized as follows:

Current	Across Track Beam Divergence	Spot Size on Polaroid Film	Recorded Track Width at 63,500cm/s On AGFA 10E75 Film
435 mA	5.4°	8.8 x 25 μm	18 μm
495 mA	10.7°	8.8 x 46 μm	38 μm
550 mA	14.3°	11 x 62 μm	50 μm (estimated)

The actual track widths recorded on AGFA film were included for the sake of comparison. This data indicates that by increasing diode current from 435 mA to 550 mA, the track width increases 3-to-1. Measurements on the diode show that output power increases 10-to-1 over the same range. Therefore, the gain in useful record spot power for a constant spot width is about 3.3-to-1, rather than 10-to-1 as might be expected from the power measurements.

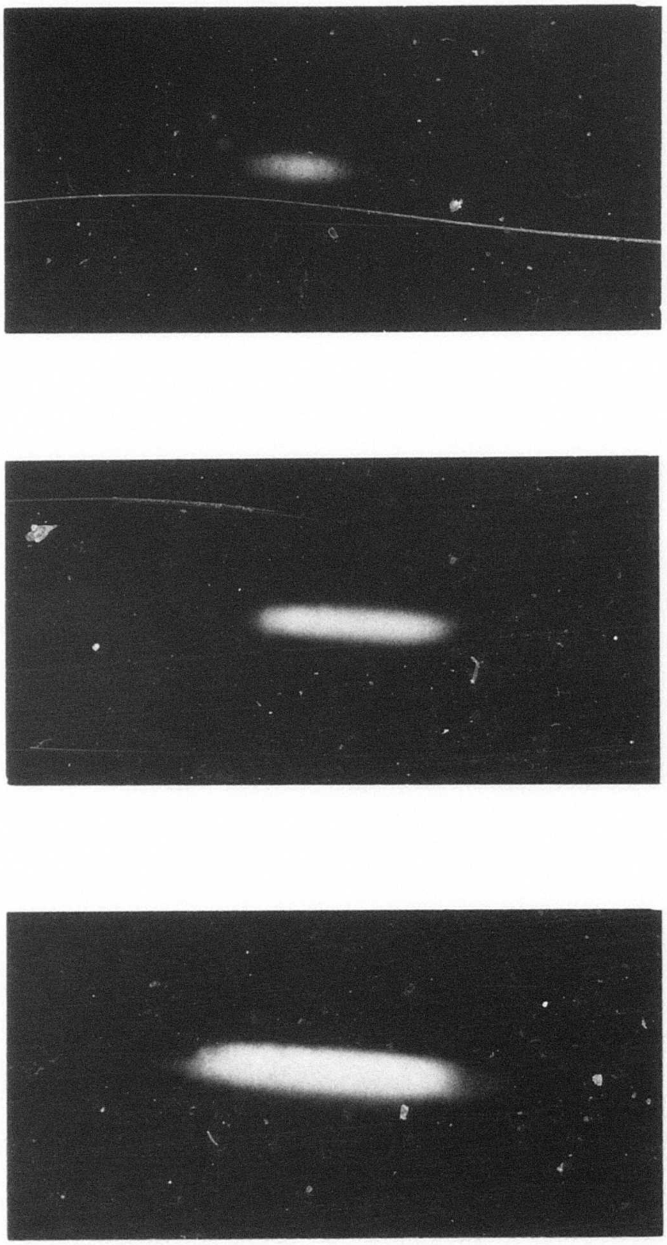


a. 435 mA

b. 495 mA

c. 550 mA

Fig. 8. Laser diode beam pattern at various current levels.



a. 435 mA
8.8 x 25 μm

b. 495 mA
8.8 x 46 μm

c. 550 mA
11 x 62 μm

Fig. 9. Simulated record spot at various current levels

The above example points out the importance of source radiance in film recording. Radiance is measured in W/cm^2sr and can be viewed as the power collected by the lens nearest the source, divided by the source area and the solid angle subtended by the lens from the source. If the diode output power is tripled by tripling the length of the lasing junction, the source radiance has not changed. If we consider the optical system to be basically re-imaging the diode junction onto the film, the spot size in the track width dimension will also triple, requiring three times more power to record. Fortunately, the data indicates that the diode radiance increases 3.3-to-1 over the useful current range.

The track width variations noted above are not expected to be a serious problem in a signal recorder. However, aperturing would be required to more closely control spot growth in direct image recorders, since it is generally desirable to have the same MTF in both the along-track and across-track directions.

Figure 11 is an extended exposure of the record spot, demonstrating the diffraction limited spot quality obtainable. The $(\sin x/x)^2$ intensity pattern characteristic of a uniformly illuminated rectangular aperture is distinctly visible. Within the accuracy of the measurements made on the pattern, the record spot is diffraction limited in the along-track direction.

2. Collection Efficiency

In view of the wide beam divergence in the along-track direction (perpendicular to the plane of the junction), a fast collection lens is required. The focal length of this collection lens should be reasonably long so that the finite source size is not a problem. In addition, this lens should have a 50-mm diameter to match well with existing record optics. A 50-mm diameter, 100-mm focal length, f/2 lens was selected. An analysis (given in Appendix A) shows that 72% of the light emitted by the laser is collected by this lens. The fan-shaped diode output beam is converted to a collimated beam of rectangular cross section. The residual divergence of the collimated beam is 5 X 250 microradians.

3. Spot Size Calculations

Assuming the existing f/2.8, 150-mm focal length, spot forming lens is used, record spot sizes can be calculated. The mirror size is .485 inch and the throw is 2.2 inches yielding the following results:

	Along-Track	Across-Track
Junction size	.5 μm	13 to 30 μm
Diffraction limited spot size	6.5 μm	6.5 μm
Geometrical spot size	1.5 μm	19 to 45 μm

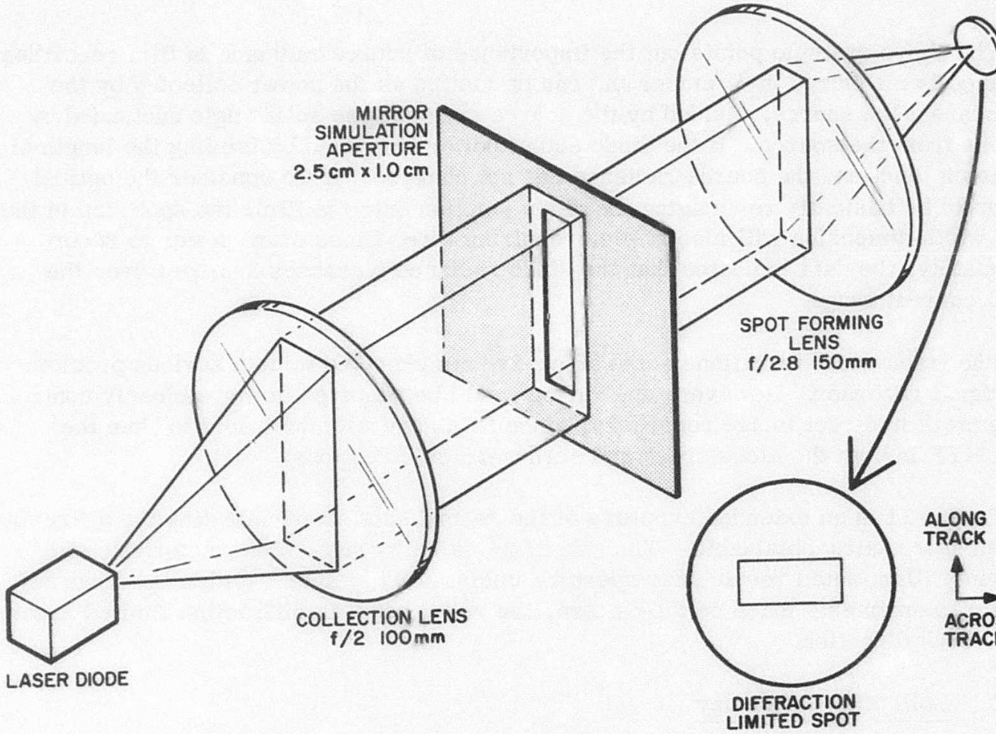


Fig. 10. Optical system bench test.

Fig. 11. Diffraction limited record spot.

The actual spot size (the larger of the geometrical or diffraction sizes) will then be 6.5 μm by 19 to 45 μm. This is in fair agreement with the measurements made on Polaroid film given in Section IID-1. A 25-μm track width was selected for design calculations.

E. SUMMARY OF DIODE TESTS

The sets of diodes were supplied by RCA Laboratories at Princeton, N. J. All were double heterojunction (AlGa)As devices capable of CW operation at 77°K. The first set were broad area contact devices with an emission wavelength of 716 nm. The second set were stripe geometry devices with an emission wavelength of 750 nm. The third set were also stripe geometry devices with an emission wavelength of 710 nm. The first set emitted at a wavelength compatible with existing films but were not specifically designed for this application. These devices were not constructed with the low thermal resistance required for extended CW operation, and their lifetime was thereby limited. No lifetime difficulties were encountered with sets 2 and 3 although individual diodes varies considerably in output power, beam shape, and threshold current. Diodes from set 2, although incompatible with high resolution films because of their emission wavelength, were used extensively to obtain modulation data. Diodes in set 3, ideal in wavelength, power, and beam divergence, were used for film recording and playback. Unless otherwise noted, data presented in this report was taken using liquid nitrogen as a coolant (77°K).

A summary of diode characteristics is given in Tables I, II, and III. The data presented is from the best diode of each set. The power input refers to the electrical power as calculated from:

$$P_{IN} = EgI_D + I_D^2R$$

as explained previously in Section II C. The power efficiency is the ratio of light out to power in, calculated at maximum output power.

A characteristic curve for the best diode in each of the three sets is given in Figs. 12, a, b, c. The bias point and the ac signal swing used in modulation tests (Section III) are noted on Fig. 12b. Some random shifts in threshold current were encountered on a day-to-day basis with the set-3 diodes due to their increased power dissipation. The cause is not believed to be a problem in the diode but changes in the thermal resistance between the diode fixture and the copper plug brought on by temperature cycling. Multimode beams occurred in all diodes above threshold, and some small effects were noted in the recordings (see Section IV E). Spurious spectral components due to longitudinal or transverse mode beats (laser noise) were not encountered with any of the laser diodes. The (c/2L) beat of frequency for diode lasers

TABLE I. DIODE CHARACTERISTICS

	Diode Geometry	Emission Wavelength (nm)	Beam Divergence Along-Track	Beam Divergence Across-Track	Maximum Light	Available Modulation
Set #1 Batch VL-476 (Diodes #1 & #4)	Double-heterojunction, Broad area contact	716	32°* (at 250 mA)	18°** (at 250 mA)	8.4 mW at 250 mA	77%
Set #2 Batch CLW-11 (Diode #5)	Double-heterojunction, stripe contact	750	44°* (at 250 mA)	28°** (at 250 mA)	2.9 mW at 300 mA	60%
Set #3 Batch CLW-21 (Diode C)	Double-heterojunction, stripe contact	710	32°* (at 500 mA)	7°** (at 500 mA)	7.6 mW at 550 mA	92%

*Full angle to half intensity points
**Full angle to nulls

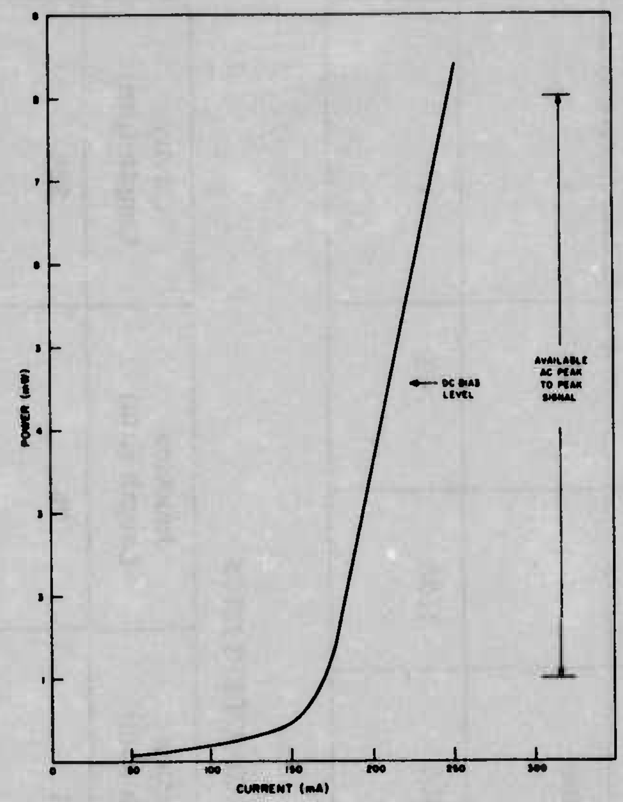
TABLE II. DIODE CHARACTERISTICS

	Threshold Current Density (A/cm^2)	Threshold Current (mA)	Maximum Current (mA)	Power Input (W)	Power Efficiency	Series Resistance (Ω)
Set #1 Batch VL-476 (Diodes #1 & #4)	900	160	300	.45	1.9%	.1
Set #2 Batch CLW-11 (Diode #5)	1800	175	300	.4	.6%	.2
Set #3 Batch CLW-21 (Diode C)	4700***	400	550	1.25	.6%	1

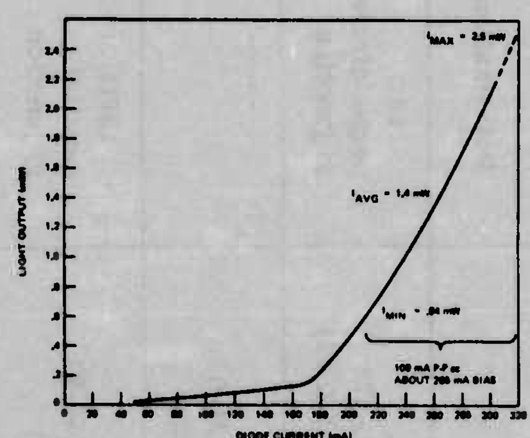
***Broad area contact version measured 2000 A/cm^2

TABLE III. DIODE CHARACTERISTICS

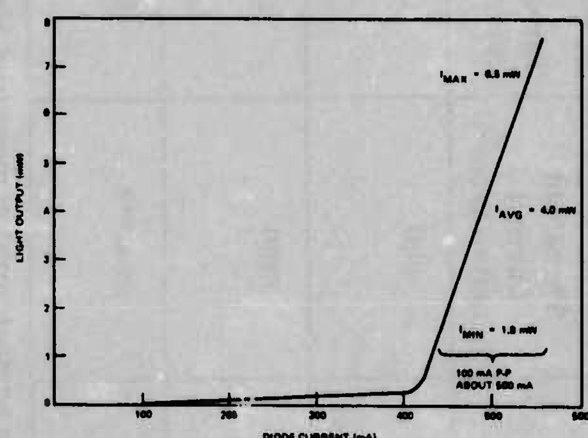
	Polarization	Junction Width (μm)	Junction Length (μm)	Cavity Length (μm)
Set #1 Batch VL-476 (Diodes #1 & #4)	18:1 perpendicular to junction	1	75	225
Set #2 Batch CLW-11 (Diode #5)	-----	.5	13-30	450
Set #3 Batch CLW-21 (Diode C)	130:1 parallel to junction	.5	13-30	330



a) Set 1



b) Set 2 (750-nm diode used for modulation data



c) Set 3 (710-nm diode used for recording

Fig. 12. Characteristic curve for the best diode of sets 1, 2, and 3.

is 500 GHz, well out of the frequency band of interest. However, one diode (set #2, modulation testing) did show a dramatic change in beam pattern at a specific current level. A general increase in the noise floor was detected at this current. For the diode used for recording, the bias had to be carefully tuned to minimize harmonic distortion, a peculiarity of this diode only. In view of the comments made with respect to the variation between diodes in the same set of samples, it should be realized that these diodes were randomly selected developmental devices.

SECTION III

WIDEBAND MODULATION EXPERIMENTS USING A LASER DIODE

A. SWEEP AND SINGLE TONE TESTS

1. Test Setup

The diode used for modulation experiments was diode #5 of set 2. The characteristic curve for this diode was shown previously in Fig. 12b. This curve shows that for a bias current of 265 mA and an alternating current of 100 mA p-p, the maximum light output (I_{max}) is 2.5 mW and the minimum light output (I_{min}) is 0.64 mW. The percent modulation is 60% as given by:

$$\% \text{ Modulation} = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \times 100$$

The ac contrast ratio (I_{max}/I_{min}) is 4.5-to-1. Larger contrast ratios can be obtained from the diode using a larger ac signal current at the expense of harmonic distortion.

Figure 13 shows the test setup used for frequency response, noise and distortion tests. Minimum harmonic distortion was obtained at a dc bias of 265 mA, which was used for the remaining tests. Figure 14 shows a 1- to 200-MHz sweep drive signal which was applied to the diode. The ac drive signal is equivalent to 100-mA peak-to-peak through the diode. Figure 15 shows the excellent frequency response of the detected light signal. When compared to the drive signal, the rolloff is about 3-dB over the 1- to 200-MHz range. This rolloff is due to lead inductance in the diode cooling and mounting structure, rather than to a fundamental characteristic of the laser diode.

Figure 16 shows the spectrum of a 50-MHz tone that was applied to the laser diode. The second harmonic of the drive signal is 35-dB below the fundamental. Figure 17 shows the same tone and harmonics in the detected light from the laser diode. The slot width on the spectrum analyzer is 300 kHz. The relative magnitude of the distortion component is:

50 MHz	Reference
100 MHz (2nd)	-25 dB
150 MHz (3rd)	-42 dB

This level of distortion is suitable for most recording applications and is comparable to that achieved with currently used gas laser and external laser beam

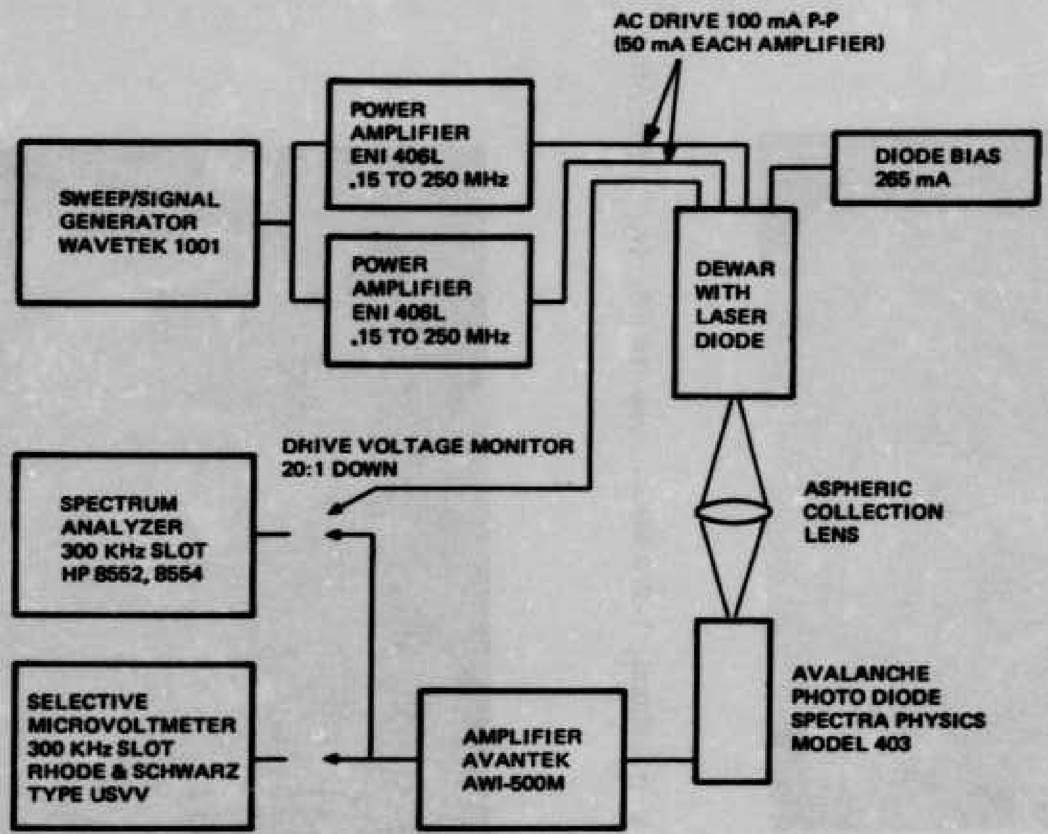


Fig. 13. Frequency response, noise and distortion test setup.

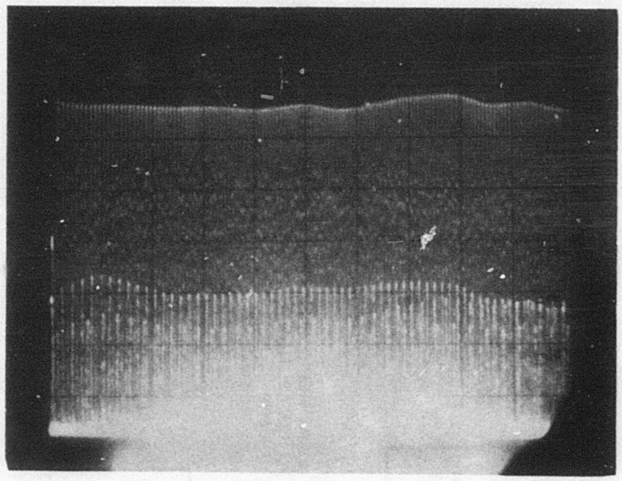


Fig. 14. Drive signal, 1-200 MHz sweep (10 dB/div, 20 MHz/div).

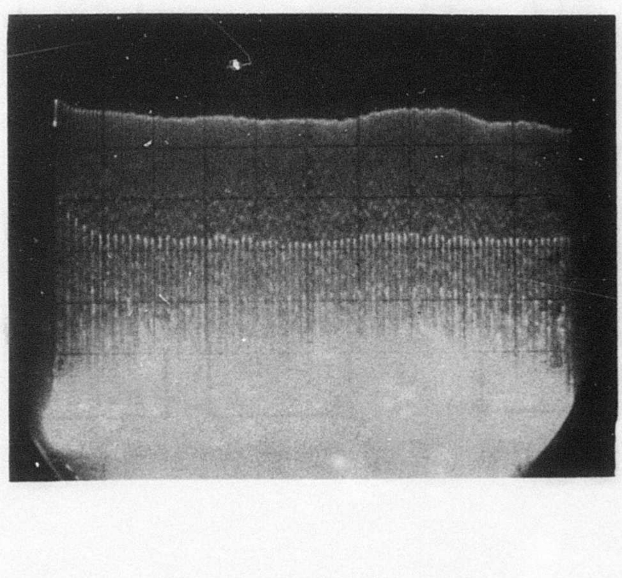


Fig. 15. Detected signal, 1-200 MHz sweep (10 dB/div, 20 MHz/div).

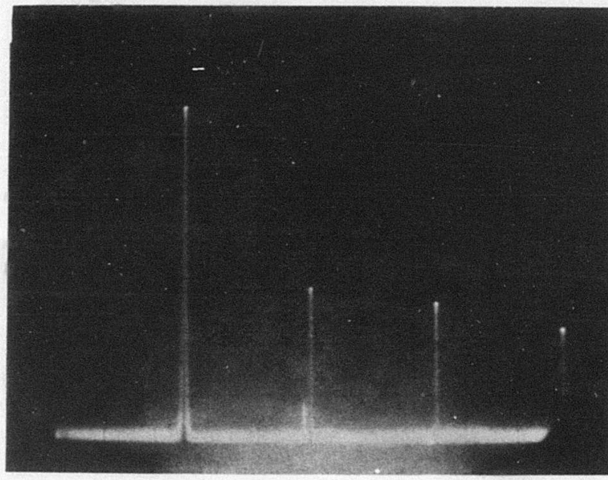


Fig. 16. Harmonic distortion, 50-MHz drive signal (10 dB/div, 20 MHz/div).

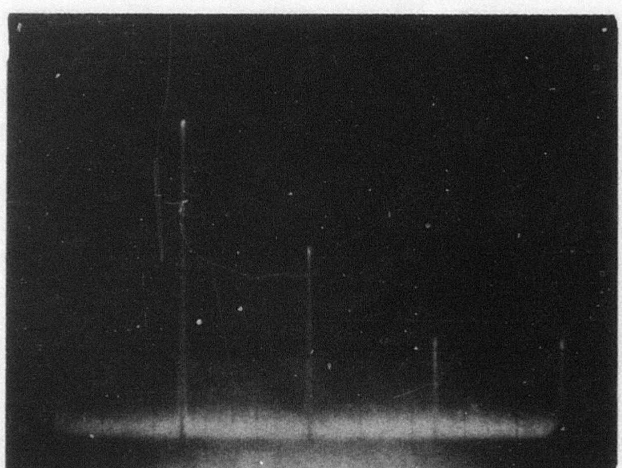


Fig. 17. Harmonic distortion, 50-MHz detected signal (10 dB/div, 20 MHz/div).

intensity modulator systems. Improved distortion levels (-30 to -35-dB down) were achieved late in the program using a diode from the third set of samples. The sweep response of the set-3 diode used for recording is compared to that of the argon laser and external electro-optic modulator in Fig. 18. A 450-mA bias and 75-mA p-p ac drive were used, yielding a 92% modulation.

2. Noise Data and Analysis - Wideband SNR

With the laser diode biased at 265-mA, and with a drive signal of 100-mA p-p at 50 MHz as described previously, the detected signal strength and the noise level were measured with a selective microvoltmeter.

Signal

50 MHz	54 mV rms	=	152.7 mV p-p

Noise Floor (at selected frequencies in a 300-kHz slot)

20 MHz	44 μV rms
80 MHz	43 μV rms
170 MHz	45 μV rms
220 MHz	43 μV rms

Therefore, the noise is 44 μV rms in a 300-kHz slot. For a 150-MHz bandwidth, the rms noise would be:

$$44\ \mu\text{V rms}\ \sqrt{\frac{150 \times 10^6}{300 \times 10^3}} = 44\ \sqrt{.5 \times 10^3} = 983\ \mu\text{V rms}$$

$$\text{SNR} = \frac{\text{P-P signal}}{\text{rms noise}}\quad \frac{152.7 \times 10^{-3}}{983 \times 10^{-6}} = 155.2$$

$$20 \log 155.2 = \underline{43.8\ \text{dB}}$$

which is quite satisfactory for laser recording applications.

B. WIDEBAND FREQUENCY MODULATION

A wideband frequency modulator and demodulator were included in the laser diode test setup as shown in Fig. 19. The reason for using FM modulation in wideband recording systems are discussed in Section IV. For this test series, the nominal FM carrier frequency is set to 70 MHz and the carrier deviates 9 MHz for a 1 v change in input signal amplitude. The modulator can accommodate input signal frequencies extending from dc to 30 MHz. The modulator output is amplified

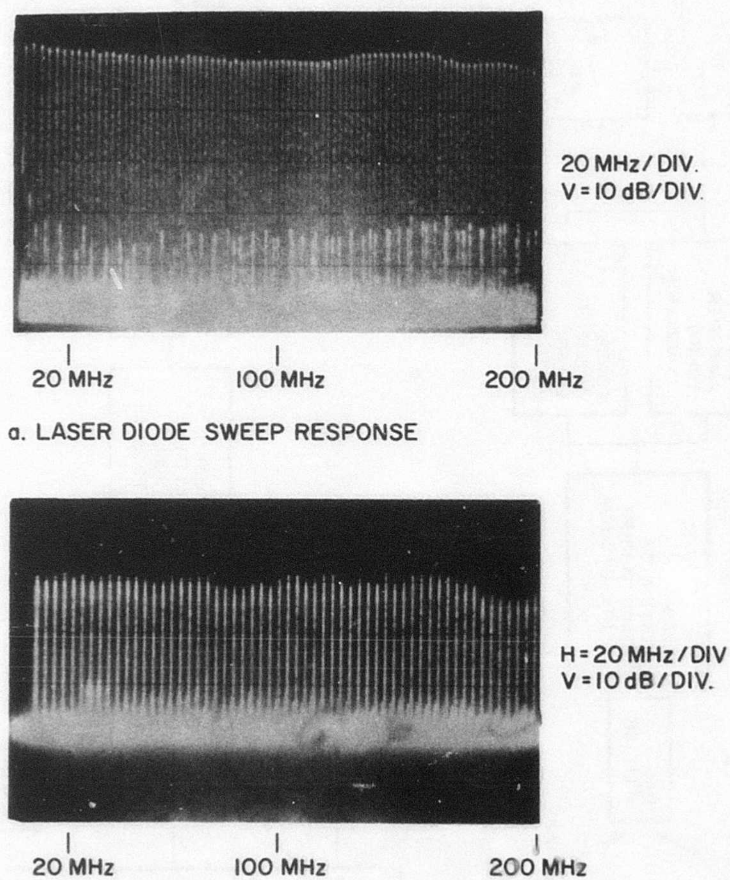


Fig. 18. Sweep response comparison.

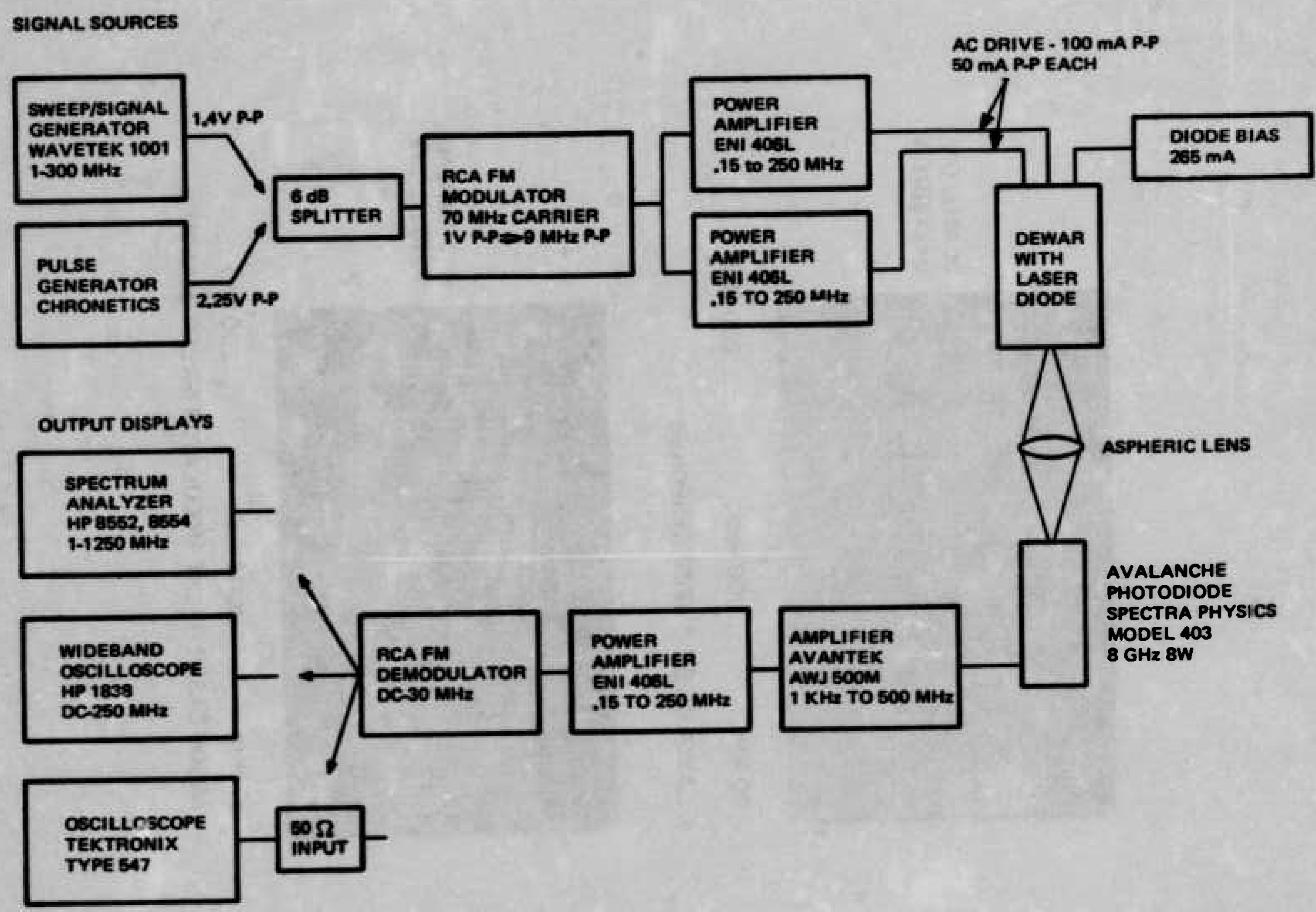


Fig. 19. FM back-to-back test setup.

and applied to the laser diode. The modulated light is detected, amplified, and then demodulated by an FM demodulator that has a 30-MHz bandwidth.

Figure 20 shows a 10-MHz input signal to the FM modulator. The second harmonic is 44-dB down. Figure 21 shows the same signal after being applied to the laser diode, detected, and demonstrated. The second harmonic is 26-dB down. Figure 22 is an oscilloscope presentation of the detected, demodulated signal.

Figure 23 shows a 1- to 30-MHz sweep signal that was applied to the FM modulator. Figure 24 shows the same sweep after detection and demodulation.

Figure 25 shows a square wave that was applied to the FM modulator. The detected and demodulated square wave is shown in Fig. 26. Figures 27 through 30 compare the rise- times and fall-times of the pulse train at the input and output of the FM system. The results are comparable to that obtained using a gas laser with an external light intensity modulator.

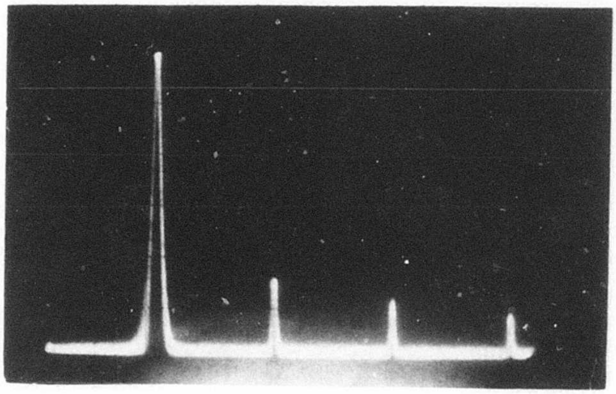


Fig. 20. 10-MHz tone input to FM modulator (1.4 V p-p, 10 dB/div, 5 MHz/div)

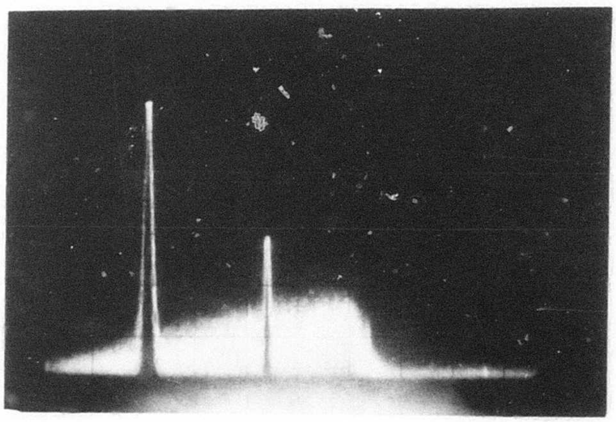


Fig. 21. Detected and demodulated 10 MHz tone (10 dB/div, 5 MHz/div)

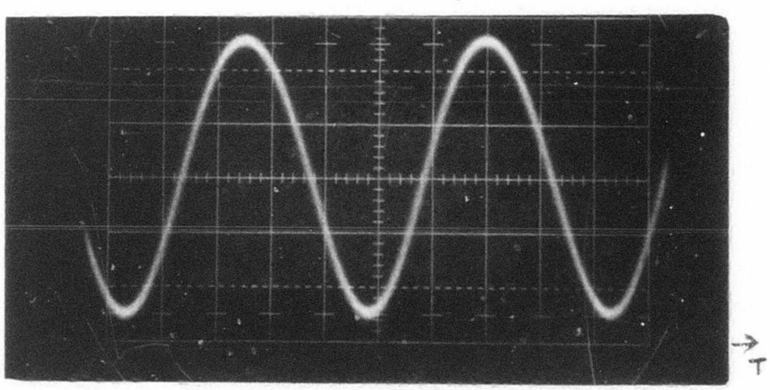


Fig. 22. Detected and demodulated 10 MHz tone (40 mV p-p, 20 ns/div)

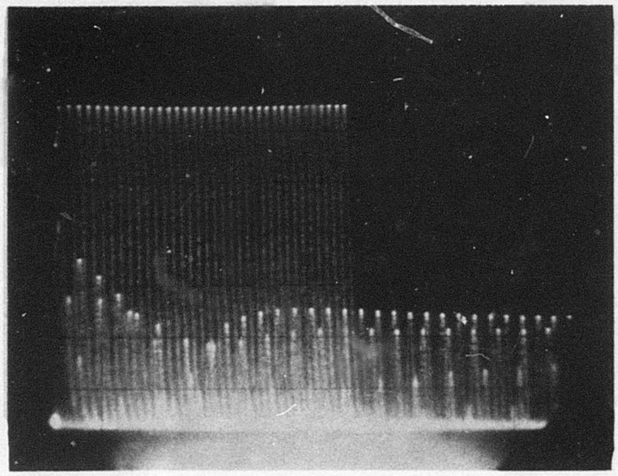


Fig. 23. 1-30 MHz sweep input to FM modulator (10 dB/div, 5 MHz/div)

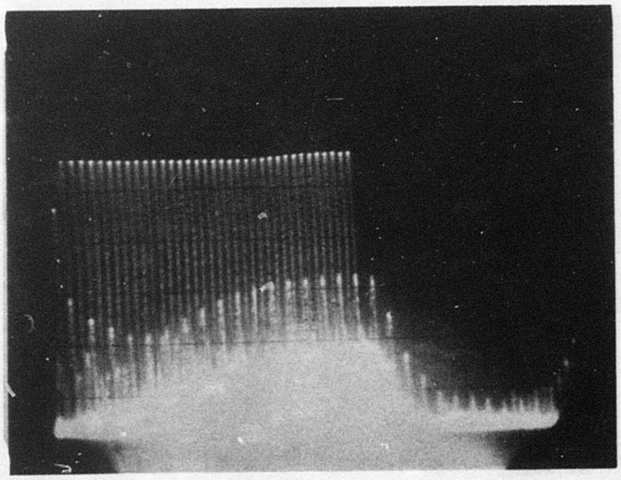


Fig. 24. 1-30 MHz sweep detected and demodulated (10 dB/div, 5 MHz/div)

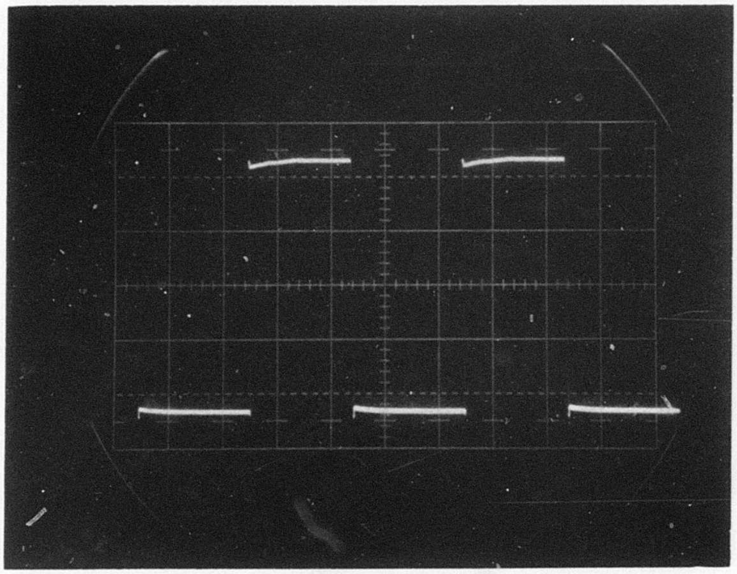


Fig. 25. Square wave input to FM modulator (0.5 V/div, 2 μs/div)

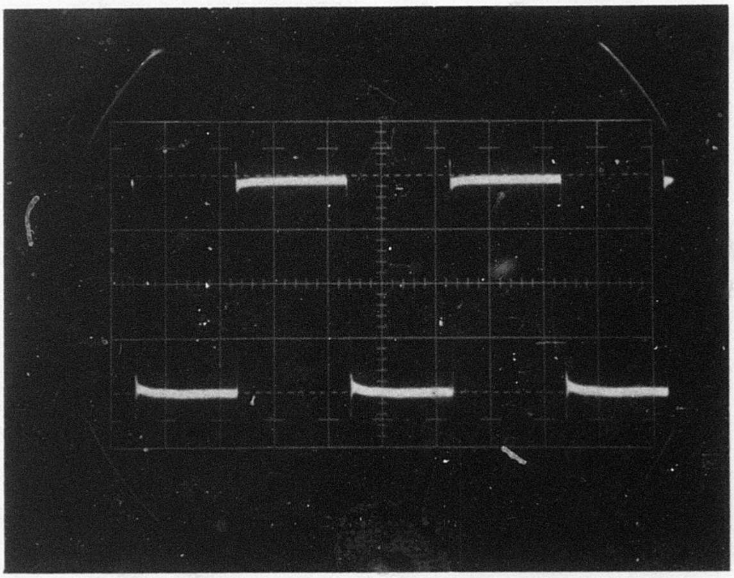


Fig. 26. Detected and demodulated square wave (20 mV/div, 2 μs/div)

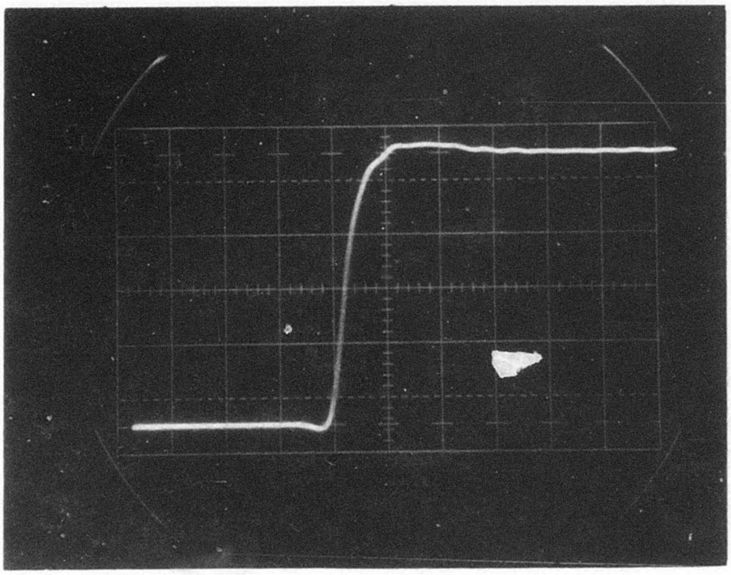


Fig. 27. Modulator input rise time (20 ns/div)

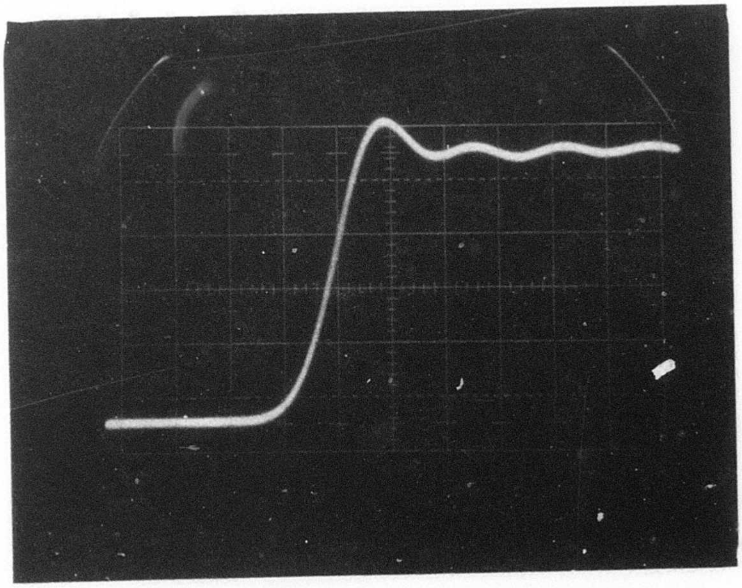


Fig. 28. Rise time after detection and demodulation (20 ns/div)

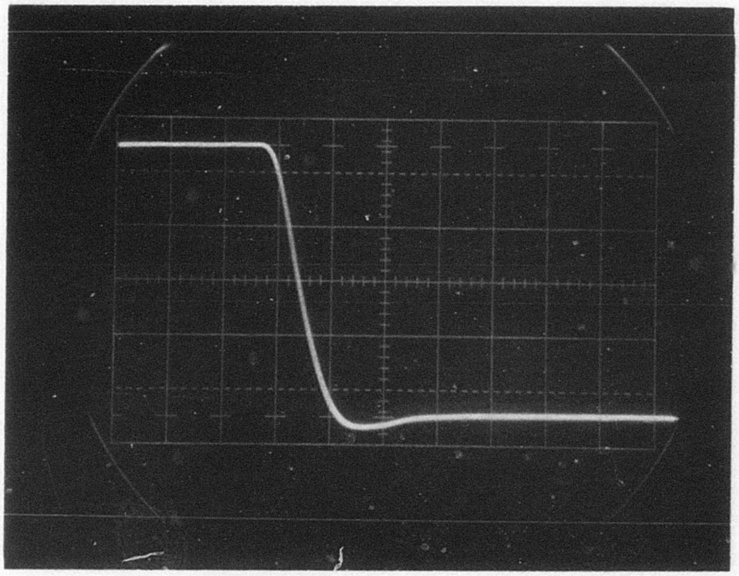


Fig. 29. Modulator input square wave fall-time (20 ns/div)

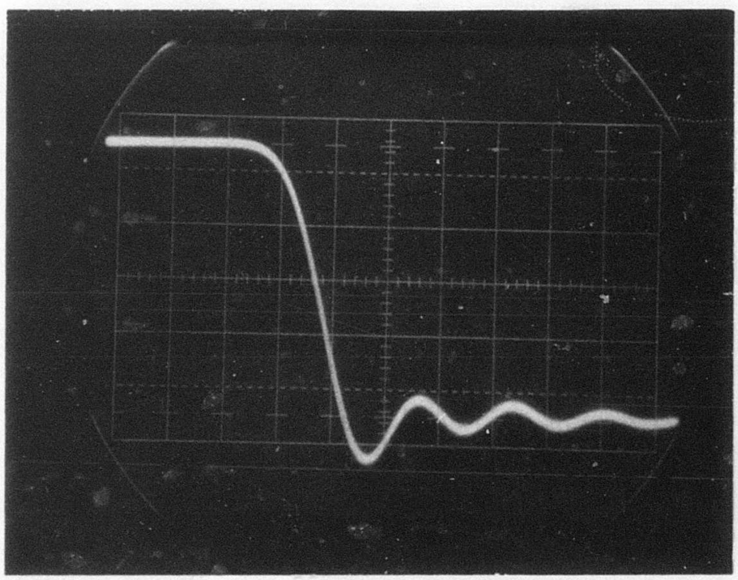


Fig. 30. Detected and demodulated square wave fall-time (20 nsec/div)

SECTION IV

FILM RECORDINGS AND PLAYBACK TESTS

A. ARGON LASER RECORDER

The original argon laser recorder,[5] which has since been modified to accommodate the laser diode source, is shown in Fig. 31. The system was developed for recording baseband data from 100 Hz to 100 MHz using laser scanning techniques. The output of an argon laser (approximately 2 W, all lines) is passed through an electro-optic light modulator where the beam intensity is modulated by the input signal information. The modulated beam is expanded to fill the imaging lens and focused to a diffraction-limited spot on the film. Two hexagonal rotating mirrors, located within the focus of the imaging lens, deflect the modulated spot in an arc at a rate up to 127,000 cm/sec (50,000 in/s). The hexagonal mirrors are positioned such that 12 film scans are achieved for each scanner rotation. Silver halide film, 70-mm wide, is transported past the scanning laser beam and is exposed along transverse tracks in a format similar to that of rotary head video tape recording. After the film is developed, it is transported past the scanning beam which once again becomes intensity modulated, this time by the transmittance variations of the film. The light is collected using appropriate optics and is photodetected, yielding a reproduction of the original signal. Using the control track information, a capstan servo incrementally aligns the tracks of the film with the scanning beam to provide continuous playback.

To overcome problems of film nonlinearity, amplitude variations, mechanical tolerances, and multi-octave response, the incoming video signal is processed with a frequency-modulation system. Signals are stored by the relative position of transmittance variations of the film, rather than by the relative level of transmittance. Upon playback, the recovered film signal is demodulated to reconstruct the original wideband analog information. To achieve FM recording of 100-MHz bandwidth analog signals, a bandwidth of over 200 MHz is required to accommodate the important spectral components of the FM signal that is recorded.

For injection laser recording, the gas laser and external light modulator were replaced by an injection laser and its cooling structure. The beam expander was removed and an f/2 collection lens was installed to collimate the output of the laser diode.

The scanner speed and FM electronics parameters have been modified from the original 100-MHz specifications under subsequent contracts. In this study, a scanning spot velocity of 63,500 cm/sec (25,000 in/s) was used for single tone recordings, and a velocity of 91,500 cm/sec (36,100 in/s) was used for FM recording. Recorded baseband data was 100 Hz to 30 MHz using a 60-MHz FM carrier. A single hexagon mirror was used for most recordings.

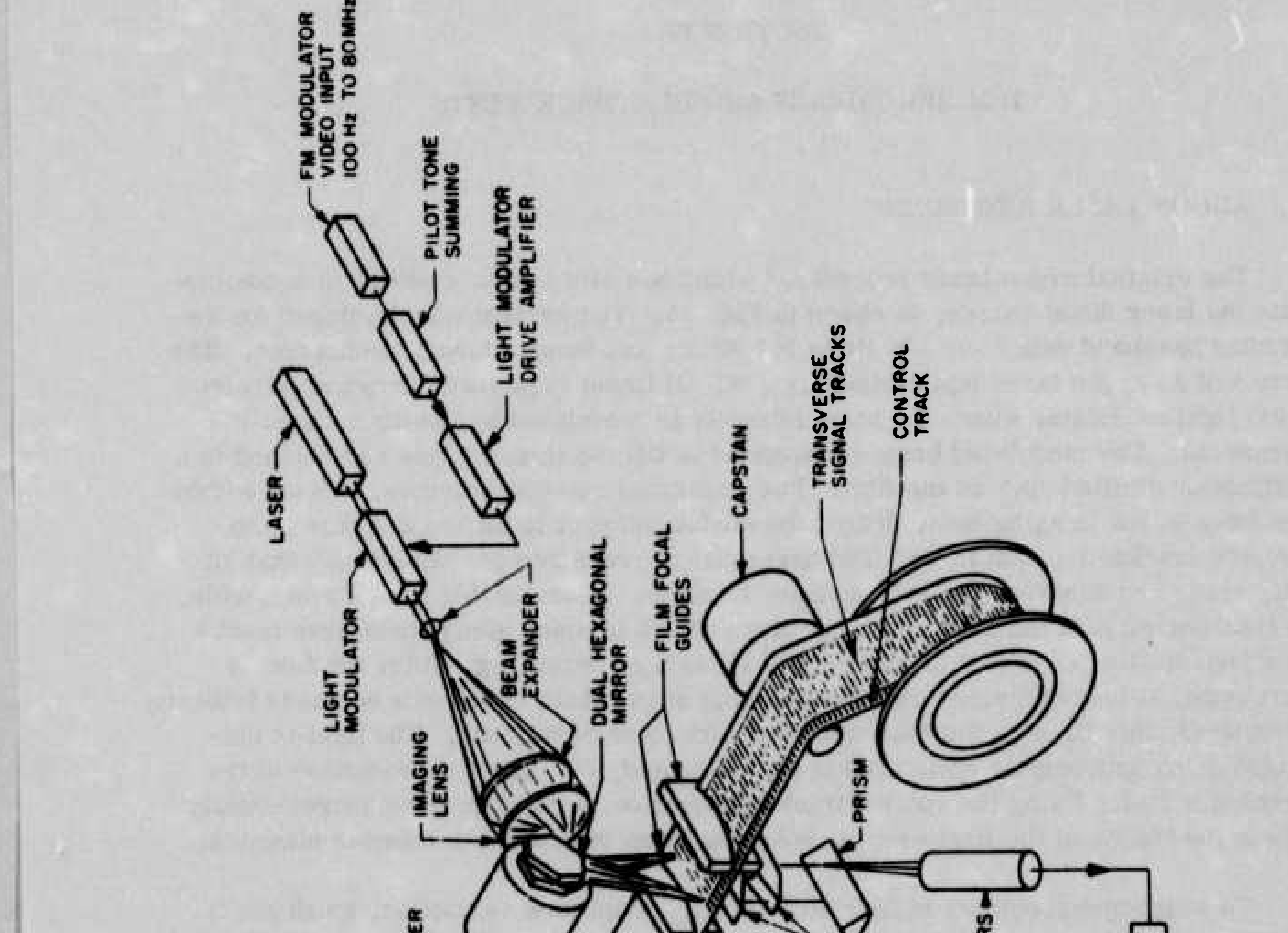


Fig. 31. Diagram of argon laser signal recorder.

B. FILM EXPOSURE REQUIREMENTS

Two, extended red, high resolution films were considered: AGFA 10E75 (50 ergs/cm^2 for D=1 at 710 nm) and Kodak SO-173 (125 ergs/cm^2 for D=1 at 710 nm). Both have good sensitivity in the 650 to 720-nm region and have granularity and MTF properties suitable for wideband recording. The spectral sensitivity curve for AGFA 10 E75, used primarily in this investigation, is shown in Fig. 32. The transmission vs. exposure data supplied by the manufacturer is shown in Fig. 33. Transmission vs. exposure data generated on the laser recorder is presented in Fig. 34, indicating that 50 ergs/cm^2 is a reasonable value for the film sensitivity at the laser diode wavelength. The laser power required in the record spot is given by:

$$P = KWV$$

Where: P = record spot power

K = film sensitivity (50 ergs/cm^2)

W = track width

V = scan velocity

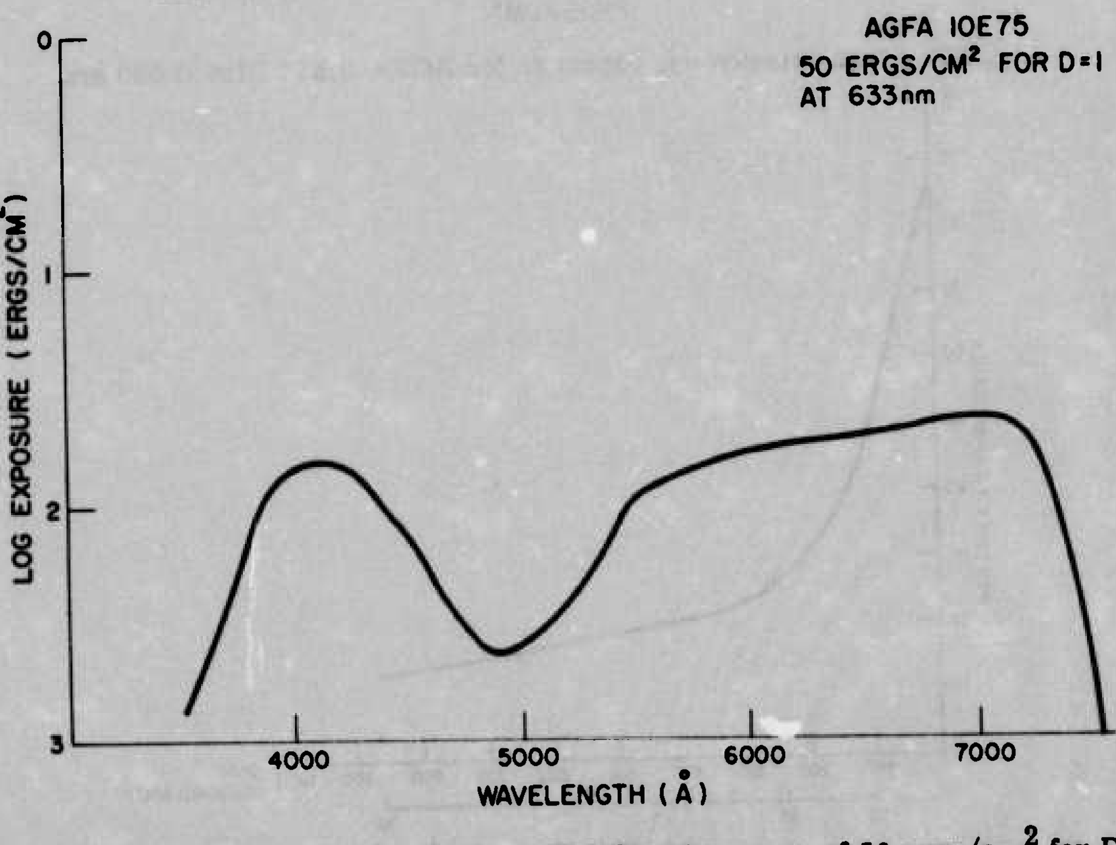


Fig. 32. Sensitivity curve for AGFA 10E75 film (exposure of 50 ergs/cm^2 for D=1 at 633 nm).

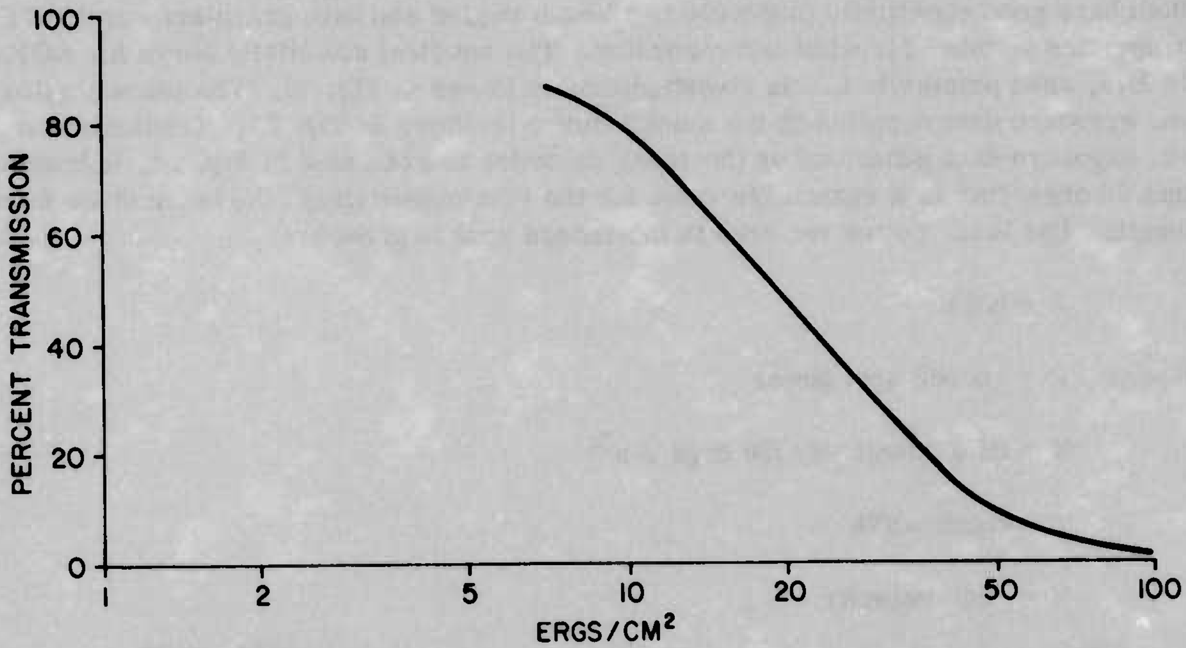


Fig. 33. Transmission vs. exposure for AGFA 10E75 film at 633 nm.

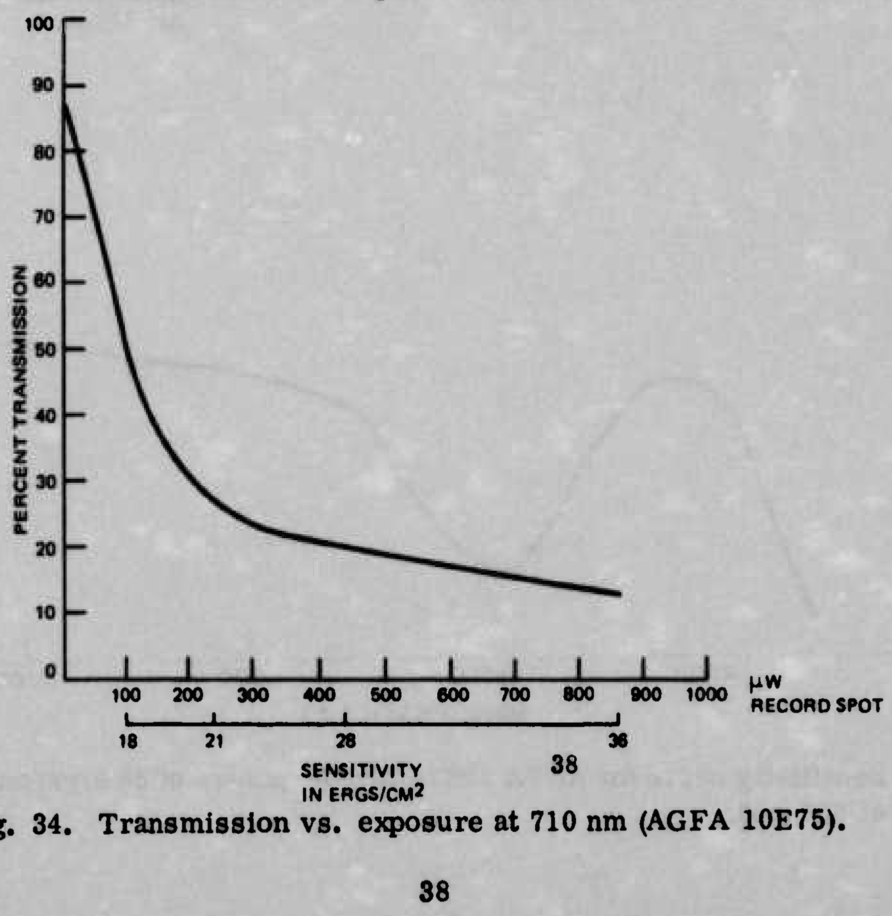


Fig. 34. Transmission vs. exposure at 710 nm (AGFA 10E75).

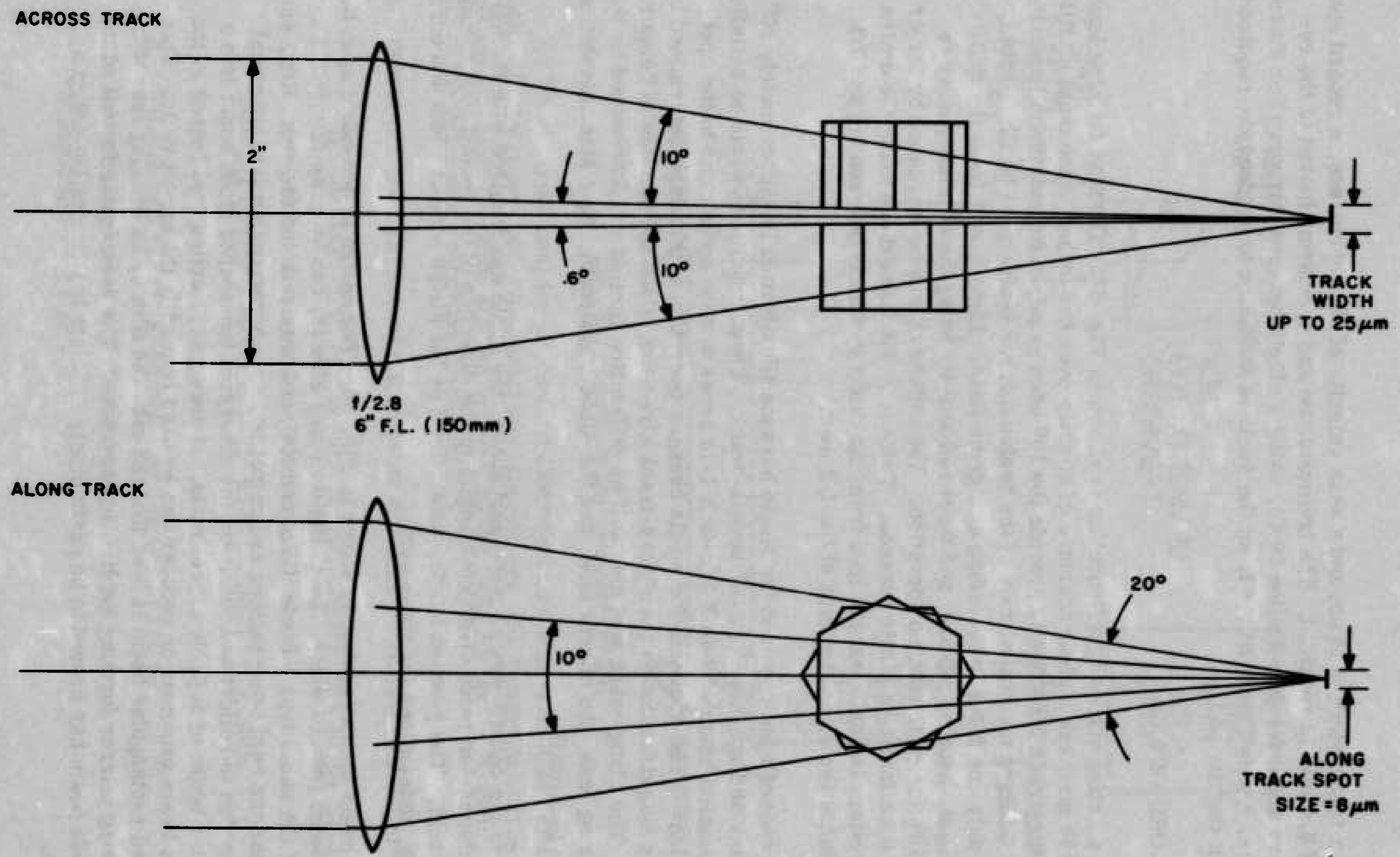


Fig. 35. Existing spot forming lens and scanner configuration.

For a track width of 25 μm and a scan velocity of 63,500 cm/sec, a record spot power of 0.8 mW is required. The transmission and aperturing losses of the recorder are about 5:1 (see Section IV C), using a single hexagon mirror. For these conditions, a 4-mW peak output from the diode is sufficient to produce the required maximum density of 1.

C. RECORD OPTICS

The existing scanner configuration is shown in Fig. 35. The spot forming lens (f/2-8, 150 mm) has a clear aperture of slightly over two inches which must be filled in the along-track direction to provide the 10^{o} cone required for maximum bandwidth. For dual hexagon operation, four of the twelve mirror facets must be illuminated, although only one facet is recording at a given time. Light losses from the multi-element lens, housing window, and facet reflectivity bring the efficiency down to roughly 10% for dual hexagon operation. The efficiency can be increased by 2:1 or more by illuminating a single hexagon. Tests with the laser diode using the entire optical system indicate that the loss from the diode to film is between 5:1 and 7:1. This includes the collection loss of the f/2 lens.

The record cone required for single hexagon illumination is approximately 20^{o} along-track and roughly 5^{o} to 10^{o} across-track. These conditions would be satisfied by a collimated beam of 2-in X 1/2-in X 1-in cross section as an input to the spot forming lens. The spot size for single hexagon operation will then be determined by the optics magnification in the across-track direction, since the junction is being re-imaged. The along-track spot size will be diffraction limited and determined by the spot forming lens, the mirror size, and the diode wavelength. Spot size calculations appear in Section II.

Due to the considerations mentioned above, the diode was mounted with the narrow junction dimension (wide divergence angle) in the direction of the record spot motion (along-track). The junction length, determined by the stripe contact width and current spreading, determines the track width.

The basic optical system is shown in Fig. 36. The design is dependent upon the emitted beam pattern which, due to multimoding effects, can be quite different for diodes of the same type. Diode 'C' of sample set 3 was selected for recording, since it exhibited the best beam pattern and output power. A reasonably fast spherical lens is needed to collect and collimate the divergent fan-shaped diode beam into a rectangular beam of suitable aspect ratio. If necessary, cylindrical lenses in the form of a beam expander or reducer can be used to modify the aspect ratio. This collimated rectangular beam is then focused onto the film by an imaging lens with the scanning mirror forming the limiting aperture. The rectangular format of the laser diode beam has proved to be particularly efficient in illuminating polygon scanners.

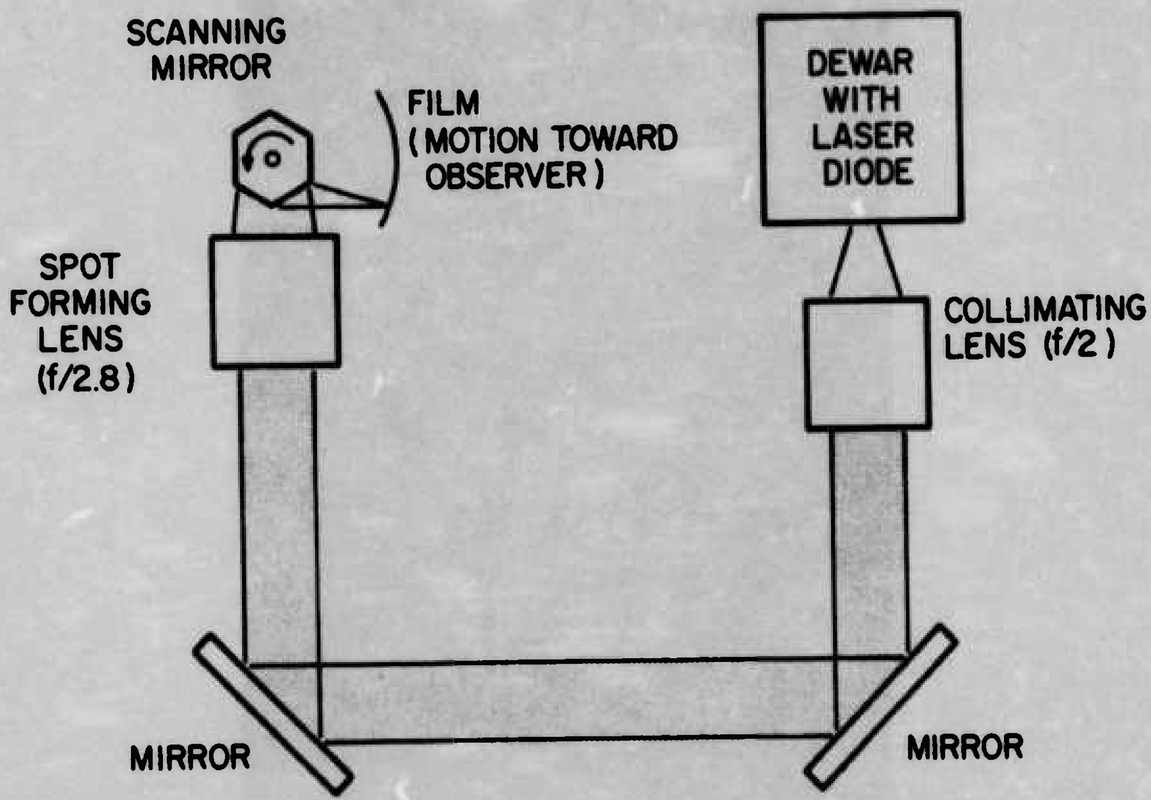


Fig. 36. Laser diode recorder optics.

An f/2 100-mm focal length, 2-inch clear aperture lens is used to collect and collimate the laser light. A special mounting fixture with 5 degrees of freedom was designed to align the diode and the driver with the recorder optical system. Fig. 37 shows the laser diode recorder breadboard.

D. SUMMARY OF SYSTEM PARAMETERS (SINGLE TONE RECORDINGS)

1. Collection lens - f/2, 10-cm focal length, collects 72% of the diode emission.
2. Imaging lens - f/2.8, 15-cm focal length.
3. Scanning mirror - single hexagon used for most recordings.
4. Spot velocity - 63,500 cm/s.
5. Film-AGFA 10E75, K=50 erg/cm^2 for D=1 at 710 nm.
6. Across-track spot size (track width) - 25 μm.
7. Along-track spot size - 6.5 μm.

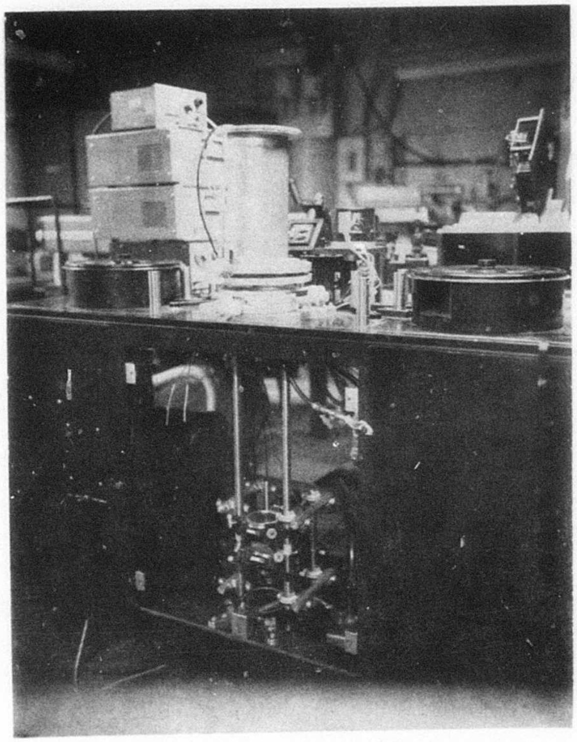


Fig. 37. Laser diode recorder.

8. Required laser power (peak) = 4 mW (Note: For continuous recording, twice this power (8 mW) is required, since two hexagon mirrors must be illuminated.)

9. Electrical drive requirements — 450 mA dc, 75 mA P-P ac.

10. Calculated record MTF at 710 nm — 250 lp/nm limiting, 125 lp/mm at 50% MTF.

11. Electrical Bandwidth - 80 MHz at the 50% record MTF point (25% record/play response).

The size of the record spot is determined by the combination of the imaging lens and the scanner mirror facet. Both the record spot velocity and the emission wavelength affect the signal bandwidth at 50% MTF.[(6)] For FM record/playback testing, the spot velocity was increased to 92,000 cm/sec, extending the 50% MTF record frequency to 115 MHz.

E. RECORD TESTS

Most of the test recordings were made using one of the two hexagonal scanner mirrors to reduce the time required to align the optical system. Single hexagon operation results in recording at a 50% duty cycle. However, both hexagon mirrors were used late in the program and a few continuous FM recordings are made. All recordings were made on short strips of film that were moved past the scanning beam by hand. No reel to reel capstan driven recordings were made.

1. Single Hexagon Tests

The light power in the record spot vs. diode current is shown in Fig. 38. A dc bias of 450 mA and an ac signal swing of 75 mA p-p, as shown, produced satisfactory single tone recordings. The contrast ratio was 25-to-1, producing a modulation of 92%. The recordings were not optimized for harmonic distortion. The average exposure control using a variable neutral density filter is desirable. Under these conditions, the peak power striking the film was measured at .73 mW while the average was .25 mW.

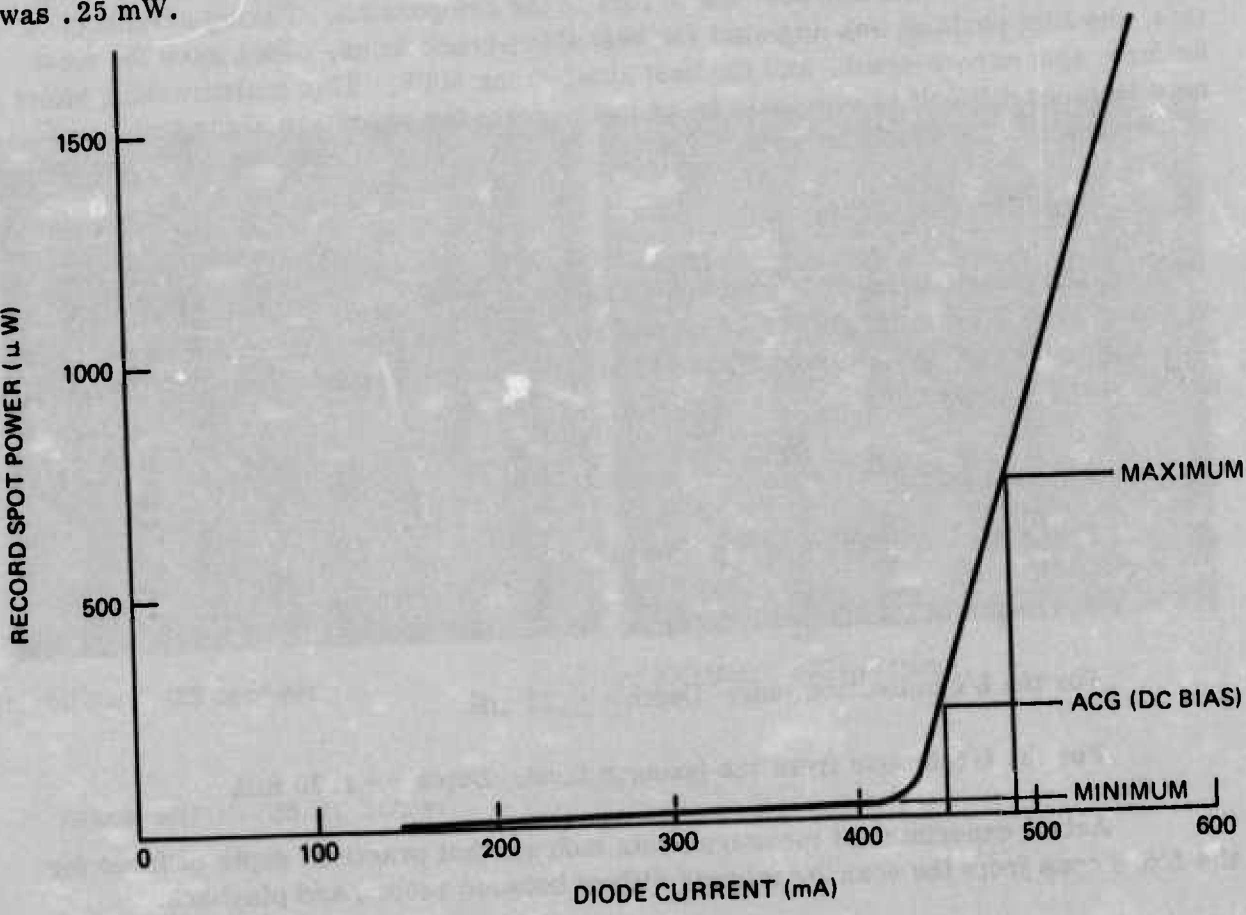


Fig. 38. Record spot power vs. current.

A series of tone recordings were made using a single hexagon at a spot velocity of 63,500 cm/sec. Figure 39 shows photomicrographs of recordings at 30, 60, 80 and 100 MHz corresponding to 50, 100, 155, 160 cycles/mm. Figure 40 shows photomicrographs of recordings made on an earlier development program[(5)] with an internally modulated laser diode and an externally modulated argon laser at 60 MHz (100 lp/mm). At this frequency the calculated recorded signal MTF is 60% for a laser diode emitting at 710 nm with a record spot velocity of 63,500 cm/s. The laser diode recording appears superior to the argon laser recording. The contrast and depth of modulation is improved, the recorded spot is well defined, and the tracks are slightly wider. The film sensitivities and granularities are comparable. The improved recordings are attributed primarily to the higher contrast ratio (25:1, see Figure 37) available from the laser diode. The ac contrast that was achieved on the wideband light modulator used with the Argon laser was 5:1 at best.[5,7]

Figure 41 shows examples of track doubling and track tripling due to the non-uniform illumination of a multimode beam. With careful focusing, it was discovered that this effect could be "tuned" out. All optical systems are slightly astigmatic due to small tilts and position errors in the components. Taking advantage of this, the film position was adjusted for best along-track focus, which gave the most uniform spot across-track, and the best along-track MTF. This multitracking effect may be more difficult to eliminate in an image recorder where the along track and across track MTF should be equivalent.

2. Dual Hexagon Tests

Dual hexagon recordings were made at 63,500 cm/sec (25,000 in/s). Figure 42 shows an FM recording of a 5-MHz square wave. The FM carrier frequency is 70 MHz and the deviation was from 35 to 105 MHz. The corresponding spatial frequencies are 55 and 165 cycles/mm.

3. Depth of Focus

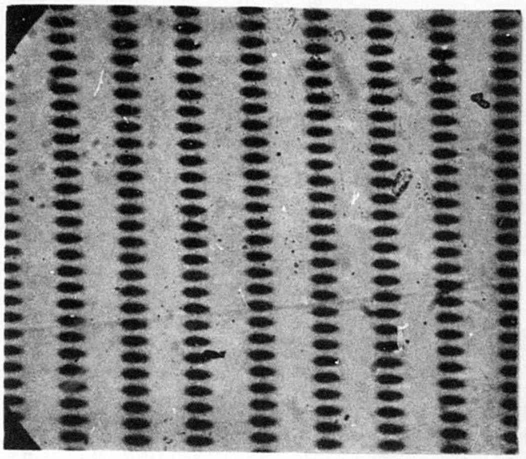
Using the Rayleigh criterion formula[8]:

$$\text{Depth of focus} = \pm 2\lambda \ (f/\#)^2$$

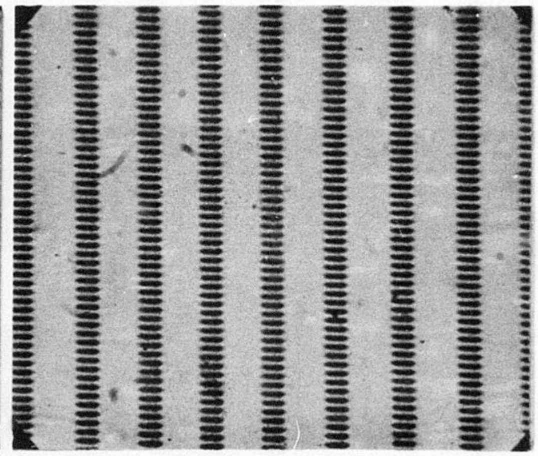
For the f/2 collection lens: Depth = $\pm$.25 mil

For the f/5.5 cone from the hexagon facet: Depth = $\pm$1.75 mil

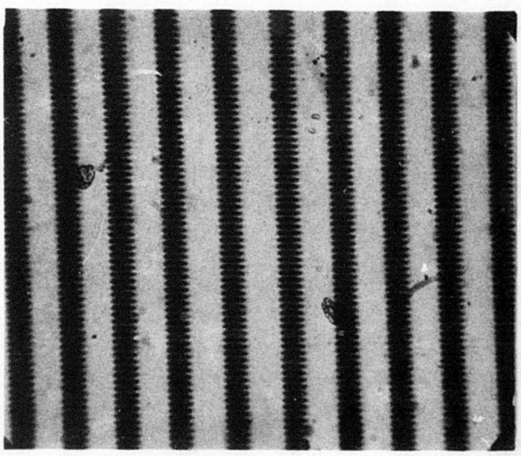
Actual experimental measurements indicate that practical depth of focus for the f/5.5 cone from the scanner mirror differs between record and playback.



a. 30 MHz 50 cyc/mm



b. 60 MHz 100 cyc/mm



c. 80 MHz 125 cyc/mm

d. 100 MHz 160 cyc/mm

TRACK WIDTH: 25 TO 30μm

Fig. 39. Laser diode recordings.

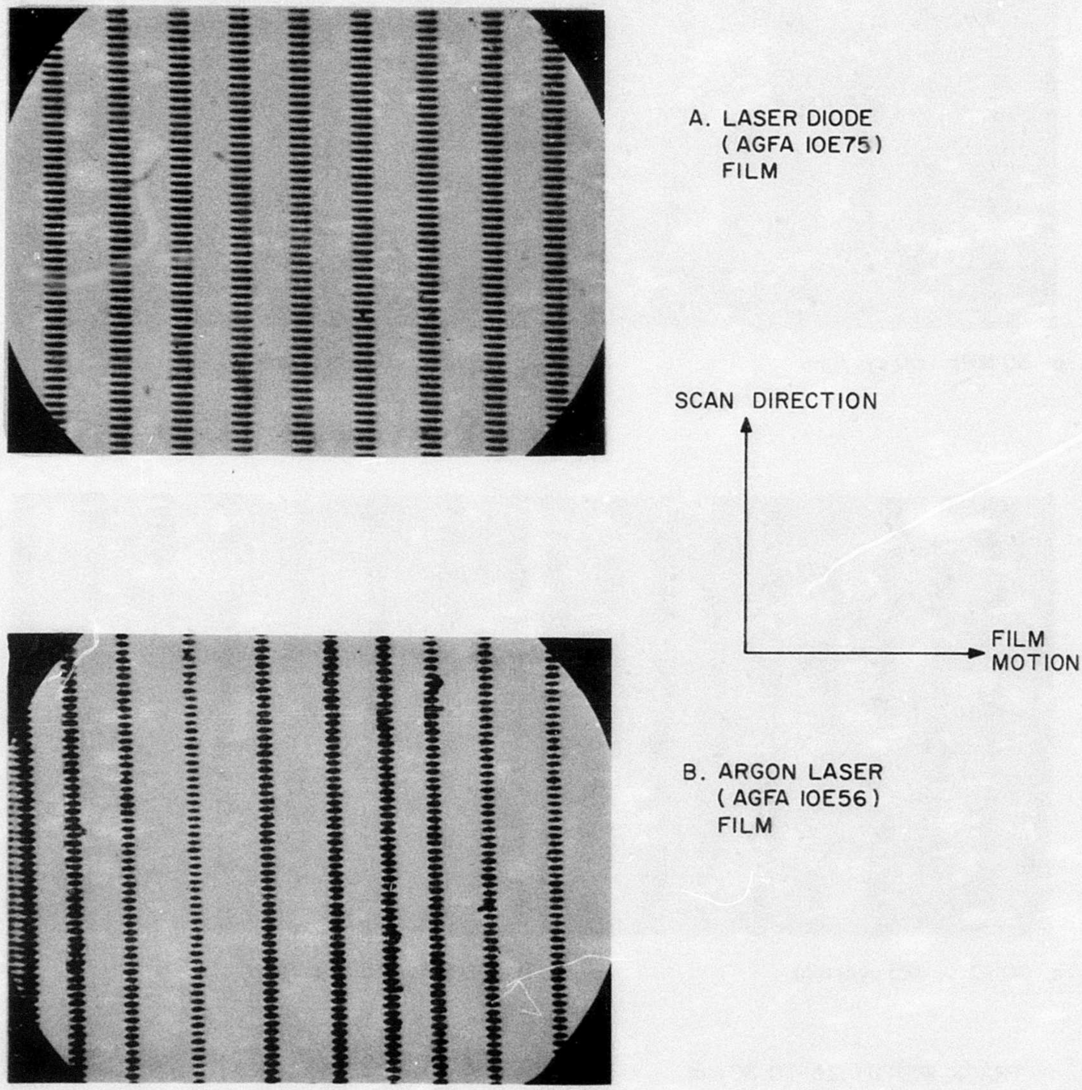
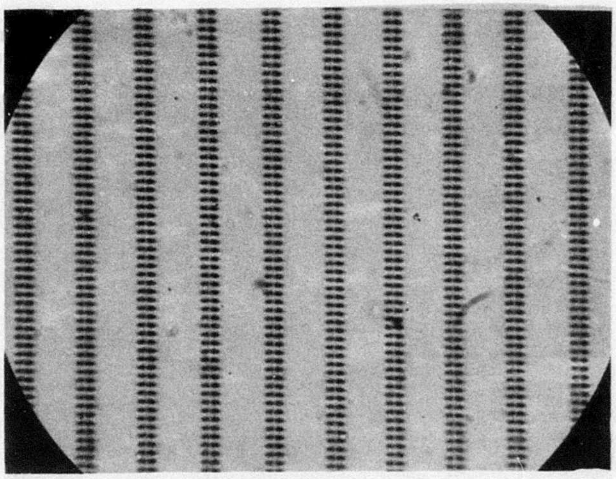
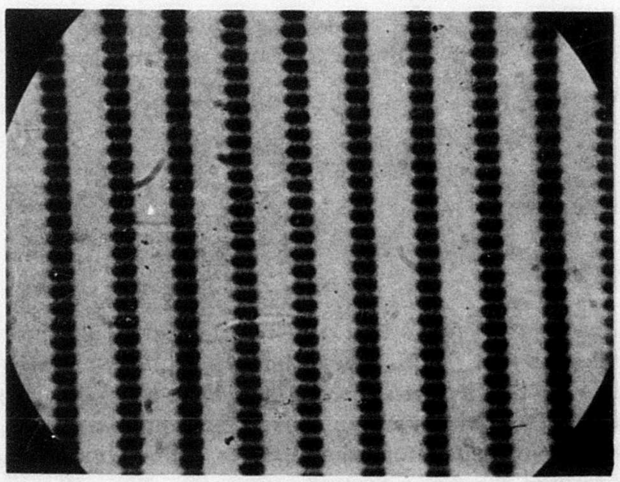


Fig. 40. Comparison of laser diode and gas laser recorders at 100 lp/mm.



60 MHz Signal Showing Track Doubling



30 MHz Signal, Triple Track

Fig. 41. Multiple tracks due to beam non-uniformity.

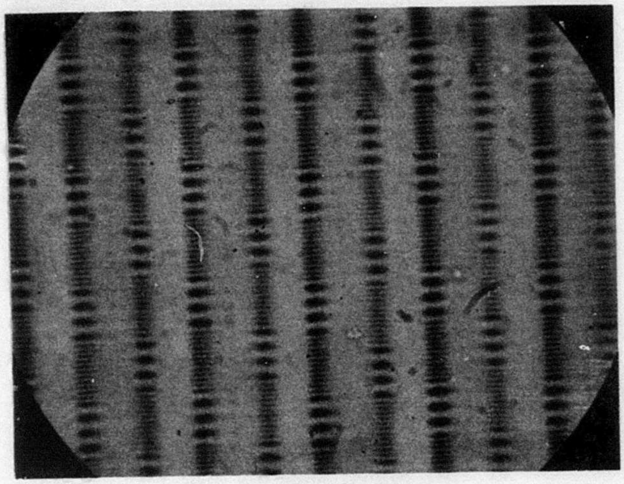


Fig. 42. Dual hexagon FM recording of a 5-MHz square wave (spatial frequencies are 55 and 165 cycles/mm).

Depth of Focus

Record — $\pm 20\ \mu m = \pm .75$ mil

Playback — $\pm 45\ \mu m = \pm 1.75$ mil

The record depth of focus is the best estimate from many recordings. The playback value indicates that the playback signal is 3-dB down from optimum focus. Both values refer to spatial frequencies of 100 cycles/mm or higher. The depth of focus of the collection lens is mentioned above since the diode is at the focus of this lens. Because of thermal expansion, the diode will move toward the lens as the level of liquid nitrogen falls in the diode cooling structure. For optimum recordings at high frequency, the liquid nitrogen level was controlled manually, however, several dewar manufacturers offer automatic refill systems.

4. Signal Level and Distortion vs. Exposure

It is generally assumed that a good recording is one in which the black and white areas are of equal length in the along-track direction. However, it may be advantageous to be slightly lighter than this criterion in order to have a good signal-to-noise ratio and low harmonic distortion. Figure 43 shows signal level vs. exposure and harmonic distortion vs. exposure. Distortion rises rapidly with exposure. Distortion on the two faintest films is suspect because it is difficult to measure due to low signal level. Measurement of such distortion is also very alignment sensitive. Normally, it would be expected that both very dark and very light films have high distortion. The eight films that were used to obtain the plots in Fig. 43 can be classed by the ratio of black to white in the along-track signal.

Film	Black-to-White Ratio	Film	Black-to-White Ratio
A	1:3	E	1.1:1
B	1:2	F	1.5:1
C	1:1.5	G	2:1
D	1:1.2	H	2.5:1

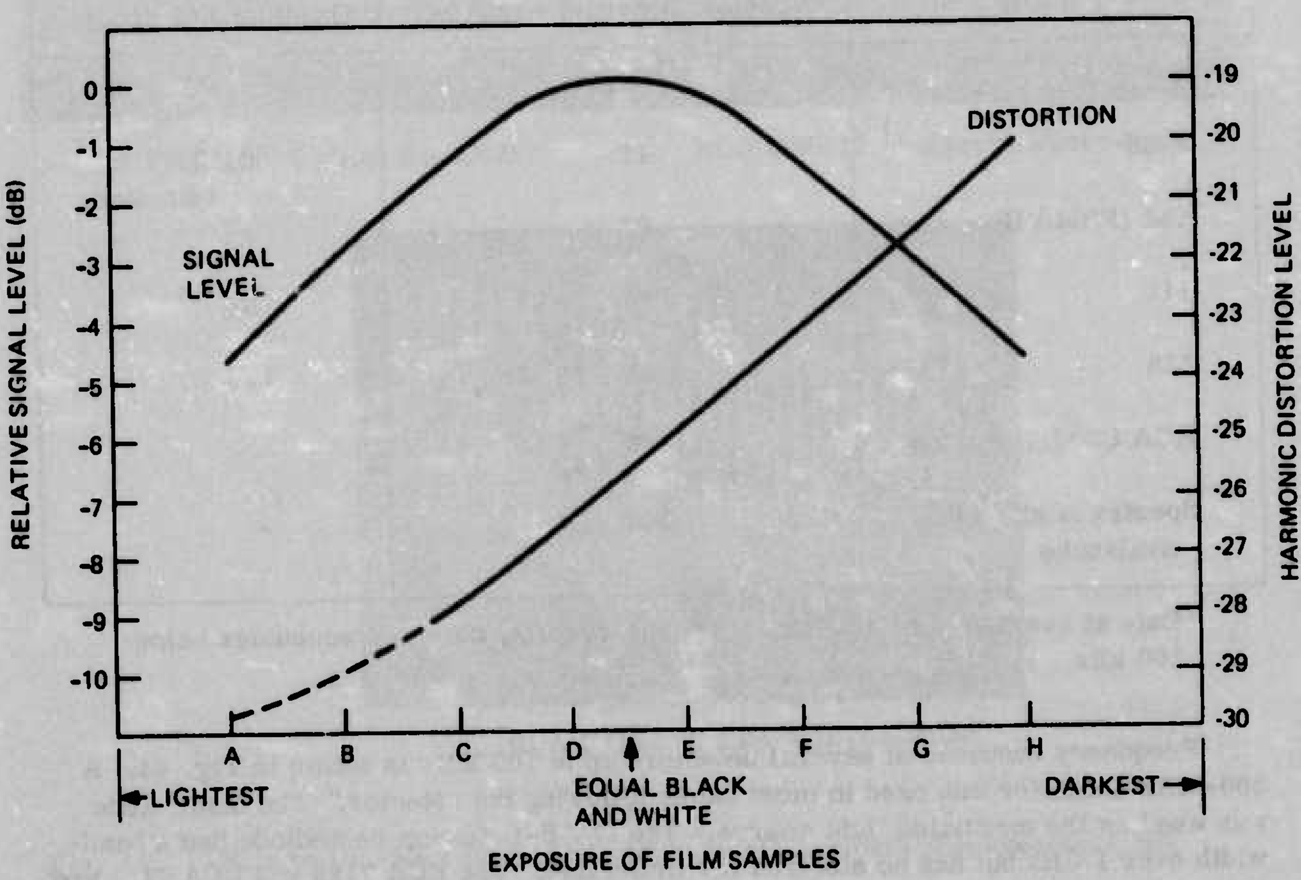


Fig. 43. Exposure of film samples.

The frequency of the recordings is 100 lp/mm. It has been observed that for higher frequency recordings, the signal level drops sharply for exposures which yield wider black areas than white areas in the along-track direction.

F. PHOTODETECTOR EVALUATION FOR PLAYBACK

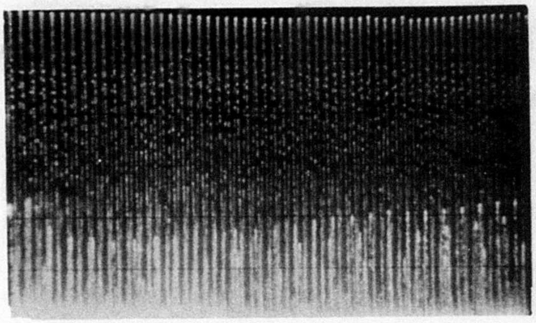
The ideal photodetector for playback would have a high sensitivity at the laser wavelength, a large sensitive area (about .25 in^2) to collect light, and a flat frequency response up to 100 MHz. No detector was found to satisfy all these requirements. The RCA C30817 silicon avalanche photodiode, although it has a small surface area, was selected as the best compromise and was used in playback tests. The Model 403 Spectral Physics avalanche detector that was used in the 10 MHz to 200 MHz modulation tests was found to have significantly reduced sensitivity for frequencies above 100 kHz[9,10]. However, the frequency response was essentially flat from 5 MHz to 200 MHz and, therefore, did not affect the modulation data presented in Section III. Table IV lists common photo-sensitive surfaces with their absolute sensitivity and quantum efficiencies at 710 nm. Also included are two avalanche detectors.

TABLE IV. COMMON PHOTOSENSITIVE SURFACES

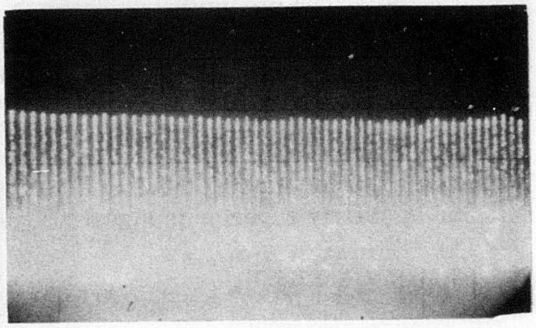
Surface	Absolute Sensitivity (mA/W)	Quantum Efficiency
S-1	2.3	.4%
S-20	12	2.5%
132 (ERMA II)	22	4%
111	30	5%
128	63	12%
RCA C30817 avalanche	65	—
Spectra Model 403 avalanche	140*	—

*Only at average light levels of a few microwatts, only at frequencies below 100 kHz

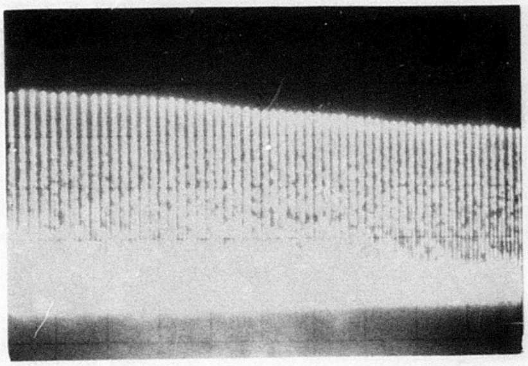
Frequency response of several detectors up to 100 MHz is shown in Fig. 44. A 500-MHz amplifier was used in most cases following the detector. The laser diode was used as the modulated light source. The ITT S-1 vacuum photodiode has a bandwidth over 1 GHz but has no electron multiplication. The RCA 7129 and RCA 7164 are



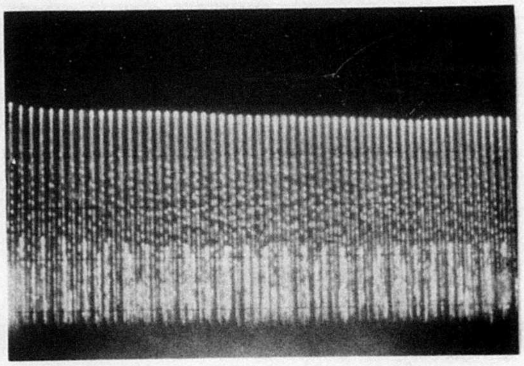
a. Drive to laser diode.



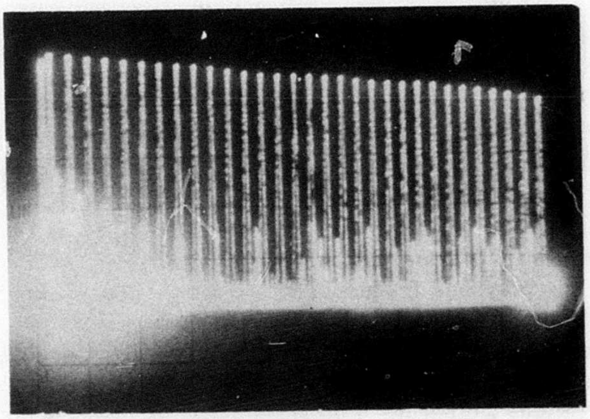
b. ITT S-1 Vacuum photodiode



c. RCA 7129 3/4" 6 stage ERMA II photo tube



d. RCA C30817 Avalanche Photo diode



e. RCA C7164 2" ERMA II phototube

Fig. 44. 1-MHz to 100-MHz frequency response of candidate photodetectors (all photos 10 dB/div, 10 MHz/div).

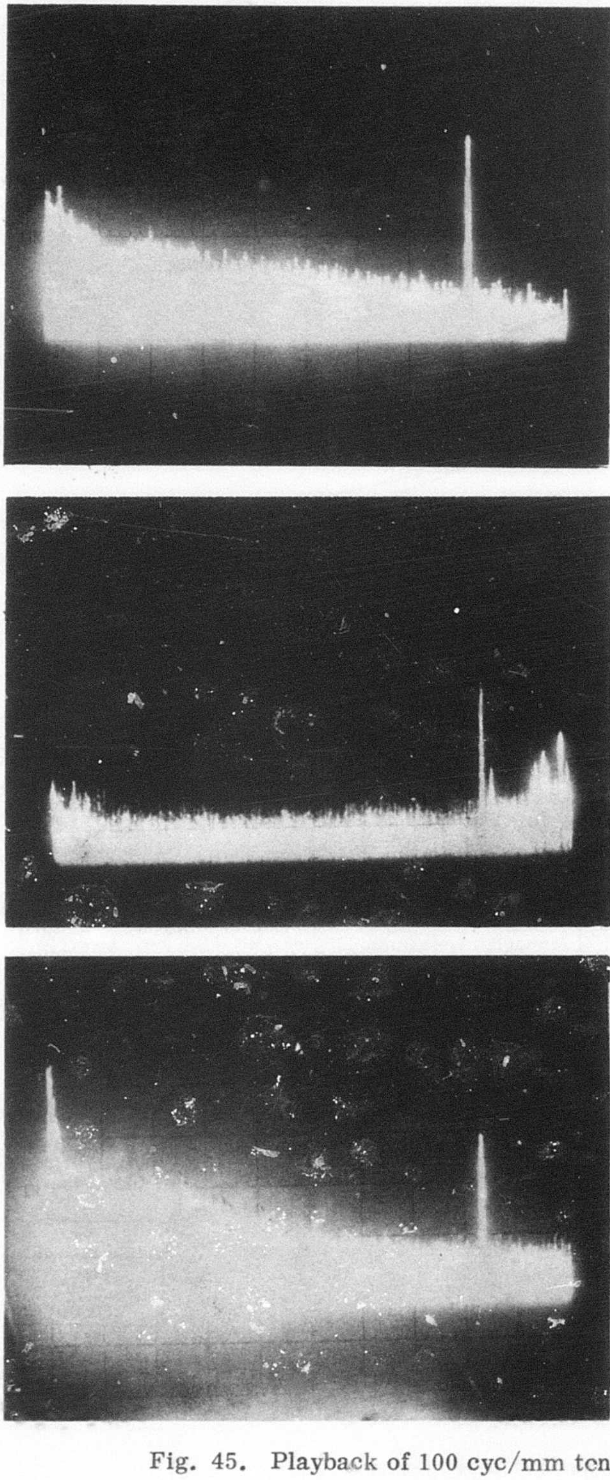
3/4-inch and 2-inch multiplier phototubes, respectively, with ERMA II photocathodes. Only six stages were used on both tubes. The sensitivity of the ERMA II photocathode is good but the frequency response is inadequate. The RCA avalanche detector appears satisfactory, down less than 3 dB at 100 MHz. The S-20 multiplier phototubes (ITT-F4008), used on the argon laser recorder were also tested but had inadequate sensitivity at the 710-nm wavelength. Figure 45 shows the playback spectrum of a 100 lp/mm tone (82 MHz) using three of the previous detectors. The RCA avalanche detector is clearly superior in signal-to-noise ratio.

G. PLAYBACK TESTS

A block diagram of the FM playback system is shown in Fig. 46. One hexagon mirror was used in playback, just as in record, yielding a 50% duty cycle signal. The light distribution through the playback optics from the two hexagon mirrors and the size of the RCA avalanche detector prevented dual hexagon playback within the time frame of this program. The laser intensity is modulated by the developed signal on the film, is collected by the playback optics, and is detected. The detected signal is amplified and then equalized to boost the upper sidebands. This signal is again amplified and passed through a 100-MHz low pass filter to the demodulator. At the output of the demodulation is a 30-MHz low pass filter. The demodulated signal is passed through the 2 X 1 switch to gate out the noise that is due to playback at a 50% duty cycle. The output of the 2 X 1 switch is applied to a spectrum analyzer or an oscilloscope. Except for measurements made on the demodulated video, noise and signal measurements were made after the first amplifier. All playback data was obtained by still-scan (film not moving) playback on short pieces of film. No timebase correction was attempted. Further details on the playback electronics are available in references 5 and 7.

1. Record/Play Response

Single frequency tones of 5, 10, 20, 30, 60, and 80 and 100 MHz were recorded at 63,500 cm/sec and used to generate the relative record/play response curve shown in Fig. 47. Since 5 MHz was the lowest tone recorded, the response relative to this frequency was found and extrapolated to zero frequency. The three abscissa scales in this figure are valid for each of the three plots. The first is spatial frequency on film in cycles/mm. The second is the frequency at which the tones were recorded and, of course, the playback frequency at a spot velocity of 63,500 cm/sec. The third scale indicates record/play response vs. frequency if the scanner speed is increased to 92,000 cm/sec. In addition to measured record/play response, the calculated optics MTF (record response) and $(MTF)^2$ (record/play response) are shown. These curves are theoretical values for a uniformly illuminated rectangular aperture. Uniform illumination is not attained in practice. It can be seen that the actual record/play response drops sharply from the calculated response at low and moderate frequencies. This generally indicates the presence of wavefront distortion, but may also



a. RCA C30817
Avalanche photodiode
10 dB/div. 10 MHz/div

b. RCA C7164 phototube
10 dB/div, 10 MHz/div

c. RCA 7129 phototube
10dB/div, 10 MHz/div

Fig. 45. Playback of 100 cyc/mm tone with candidate detectors.

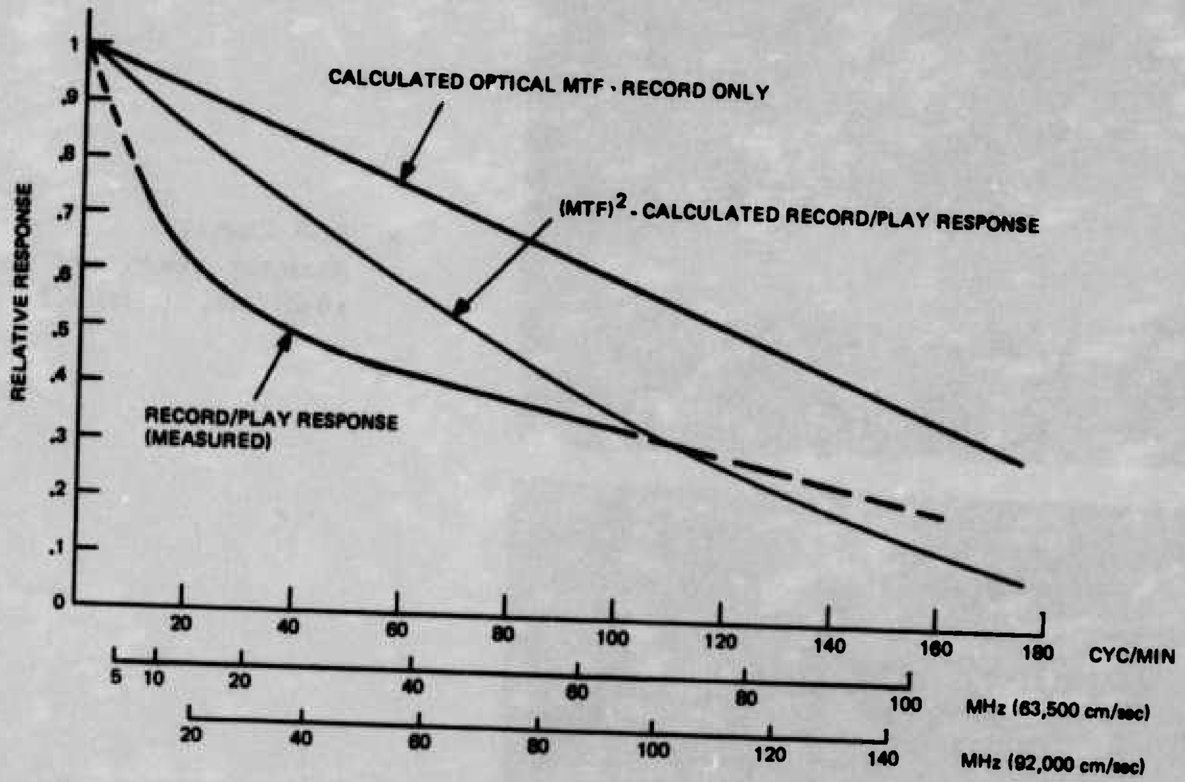


Fig. 46. Block diagram for FM still scan playback.

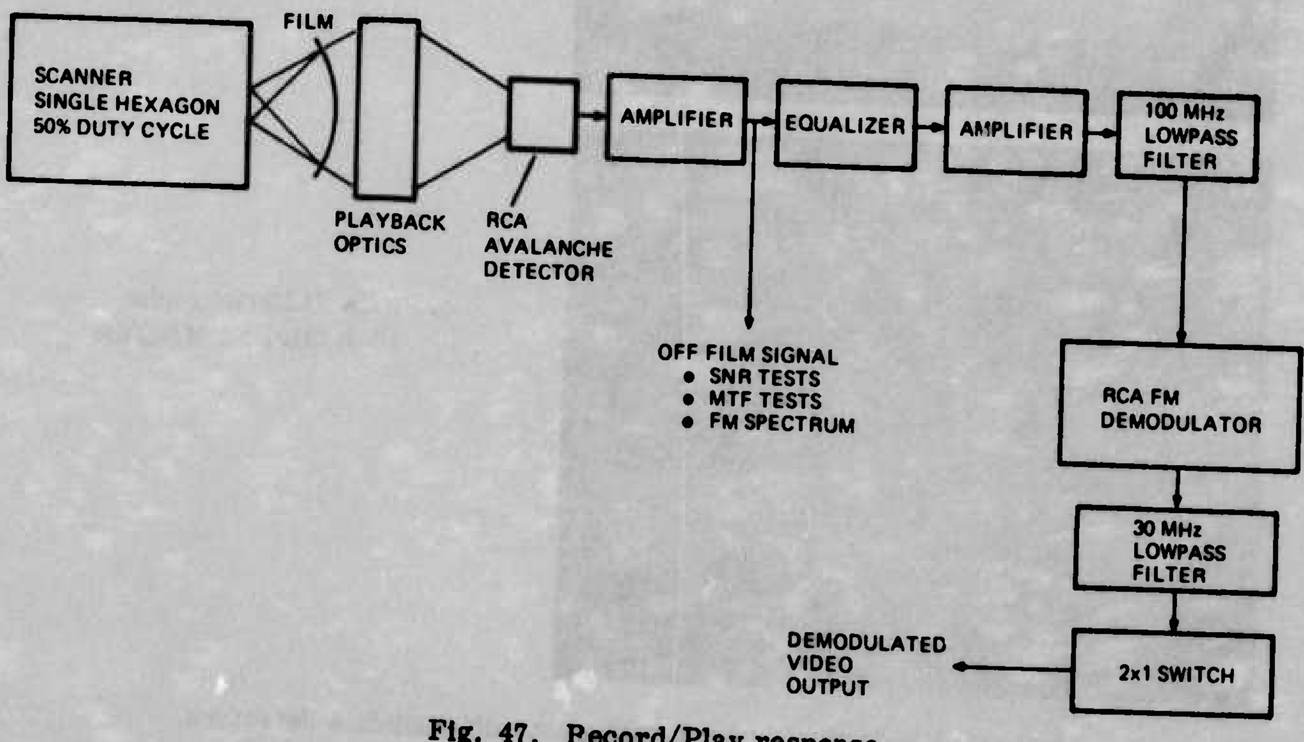


Fig. 47. Pecord/Play response.

derive partly from non-uniform illumination of the mirror facet. At the present time, it is thought that the dewar window introduces some spherical aberration (see Appendix B) which may contribute to the shape of the response curve. As a result of the MTF data, and photodetector considerations, the spot velocity was increased to 92,000 cm/sec for the FM playback tests described in part 3 of this section. The FM carrier was reduced to 60 MHz and the deviation was reduced to 33 MHz p-p. These actions were aimed at improving playback signal-to-noise ratio, and especially at improving the playback of the upper sidebands.

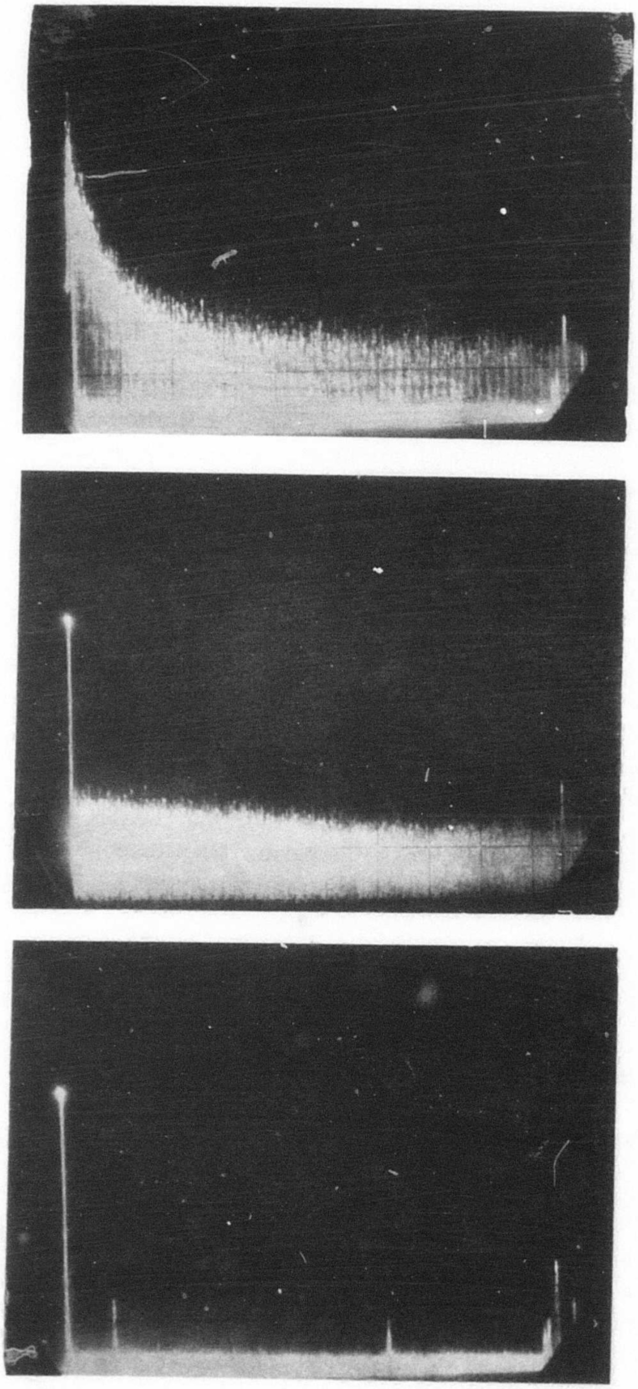
2. Noise Floor Considerations

Using only one hexagon, and therefore only a 50% duty cycle during playback, creates some difficulties in signal-to-noise ratio measurements. The limited output from the demodulator is very noisy during periods of no signal. This is the reason for the 2 X 1 switch shown in Fig. 46. In addition, signal bursts (50% or less duty cycle) pose problems for a spectrum analyzer display. These bursts will generate a $\sin^2 wt$ spectral function with harmonics separated by the mirror facet rate (~9 kHz). These spectral components appear as a rising noise floor (toward lower frequencies) as shown in Fig. 48a. The noise floor with the scanner stopped with the laser on is shown in Fig. 48b. The no-light noise of detector and electronics is shown in Fig. 48c. These measurements were made at a 63,500 cm/sec velocity with a detection system that had a 7-dB linear rolloff from 1 to 100 MHz as evidenced by Fig. 48b. The amplified detector signal is being displayed. Filter limitations and sweep speed limitations in the spectrum analyzer prevented signal-to-noise ratio measurements with 10-kHz and 100-Hz video filters on the spectrum analyzer. Instead, the signal level was measured on the 300-kHz slot and the average noise floor was measured with the 100-Hz filter in order to determine signal-to-noise ratio. Oscilloscope presentations (see part 3 of this section) are not filtered.

Reel-to-reel playback is expected to increase signal-to-noise ratio on playback, due to better track following. Figure 49a shows a still scan (film stationary) playback on the argon laser recorder. Figure 49b shows the 8 to 10-dB signal-to-noise improvement attained with accurate line following during reel-to-reel playback of the same tone. Therefore, signal-to-noise improvements of 10 dB or more are expected for continuous recordings with reel-to-reel playback. Such recordings were beyond the scope of this investigation.

3. Playback of 5-MHz and 30-MHz FM Recordings

The FM data presented here was recorded and played back at a spot velocity of 92,000 cm/sec. The FM carrier was 60 MHz with a peak-to-peak deviation of 33 MHz. This was the maximum deviation allowed for this carrier frequency for acceptable distortion and foldover effects. FM system tradeoffs are presented in detail in reference 7. Choice of carrier frequency is discussed in the part 1 of this section. The signal current to the laser diode was 500 mA p-p to assure low distortion. The contrast ratio for the FM recordings was about 20:1.

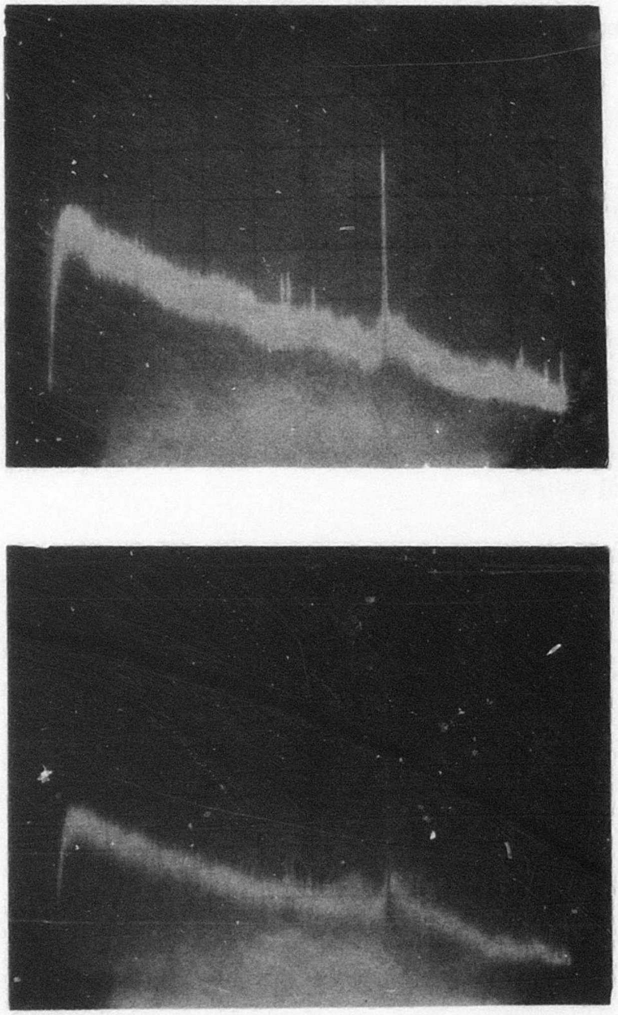


a. Noise floor-laser on, single hexagon scanner (no film)

b. Noise floor-laser on scanner stopped (no film)

c. Noise floor-no light detector and amplifier

Fig. 48. Noise floor after detector and amplifier.



a. Still scan playback 120-MHz tone 10 dB/div, 20 MHz/div. 10 kHz video filter

b. Reel-to-reel playback 120-MHz tone 10 dB/div, 20 MHz/div, 10 kHz video filter

Fig. 49. Comparison of signal-to-noise ratio between still scan playback and reel-to-reel playback for an argon laser.

Figure 50a shows the magnified film recording of a 5-MHz FM signal. Track width is 25-μm. Figures 50b, c, d, respectively show the FM spectrum on playback, the demodulated video spectrum, and the demodulated video signal. Figures 50e, f, g, h show comparable photographs for a 30-MHz FM signal. In both cases, the FM spectrum is shown before equalization. For the 30-MHz tone, the noise floor (100-Hz filter) is at -70 dBm, indicating a 42-dB rms-to-rms signal-to-noise ratio over the 300-kHz slot. This converts to 31 dB p-p to rms over a 30-MHz bandwidth. The signal-to-noise ratio and distortion of the playback signal appears equal to or better than obtained with the argon laser recorder (see references 5 and 7).

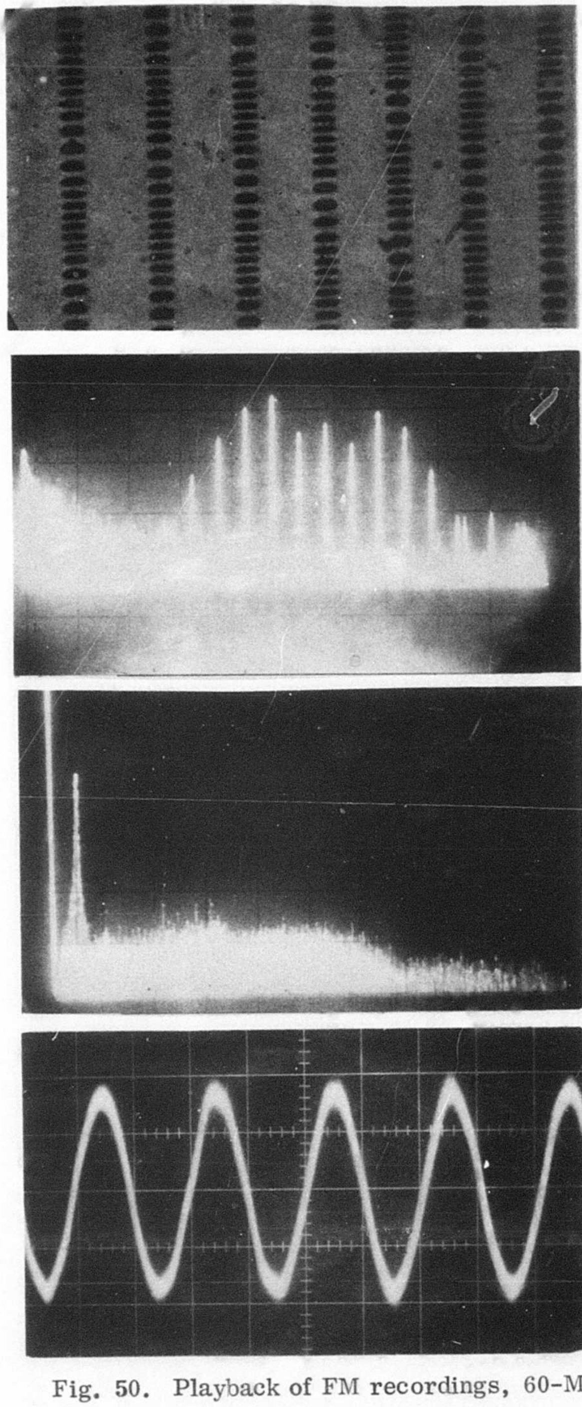
H. COMPARISON OF THE ARGON LASER SYSTEM WITH THE (Al Ga) As SYSTEM

The laser diode has been shown to produce superior quality recordings because of the increased contrast ratio of the modulated light. Substantial reductions in optical power and electrical power requirements were also noted. Ease of operation was considerably improved. Elimination of laser mode beats and external modulation for argon lasers required the reliance on sensitive electro-optical components (intercavity etalon and electro-optic modulator). These lossy components are unnecessary with a laser diode source. The diode is internally modulated and has mode beat frequencies for above the band of interest.

Table V compares the two laser systems for continuous recording (dual hexagon) at 63,500 cm/sec (25,000 in/s) spot velocity.

TABLE V. COMPARISON OF ARGON AND LASER DIODE LASER SYSTEMS

	Argon	(Al Ga) As Diode
Input Electrical Power	10 kW	10 W
Light Power Required	1 W (all lines)	8 mW
Wavelength	488 nm	710 nm
AC Contrast Ratio	5:1	>25:1
Spot Size	4.5 um x 20 um	6.5 um x 25 um
Peak Record Spot Power	0.4 mW (AGFA 10E56)	0.8 mW (AGFA 10E75)
Transmission and Aperturing Losses	2000:1	10:1
Mode Beat Frequency (c/2L)	115 MHz	500 GHz
Coolant	Water	Liquid Nitrogen
Beam Geometry	Circular	Rectangular



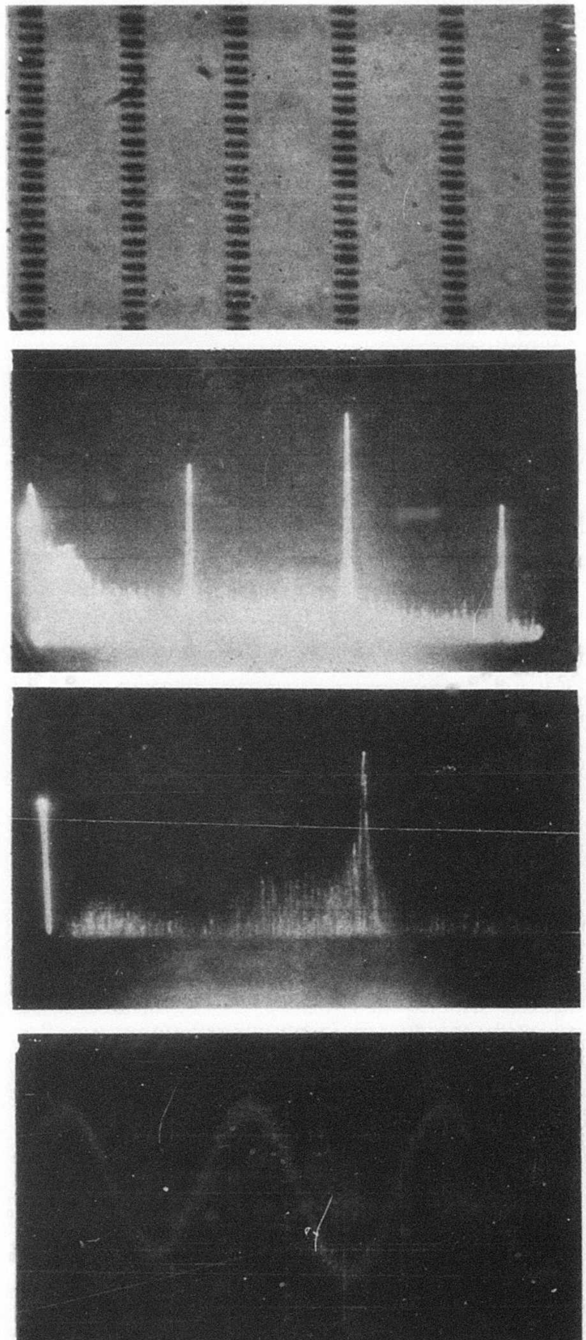
a) RECORDED TRACKS
(5-MHz FM SIGNAL)
25- m TRACK WIDTH
50 cyc/min/and
8 cyc/min

b) FM SPECTRUM
OFF FILM
(BEFORE EQUALIZATION)
10 MHz/div
10 dB/div
300 kHz SLOT

c) DEMODULATED
SPECTRUM
10 MHz/div
10 dB/div
300 kHz SLOT

d) DEMODULATED
VIDEO
SIGNAL
20 mV/div
100 ns/div

Fig. 50. Playback of FM recordings, 60-MHz carrier, 33-MHz deviation.



e) RECORDED TRACKS
(30-MHz FM SIGNAL)
25- m TRACK WIDTH
65 cyc/mm

f) FM SPECTRUM
OFF FILM
(BEFORE EQUALIZATION)
10 MHz/div
10 dB/div
300 kHz SLOT

g) DEMODULATED
SPECTRUM
5 MHz/div
10 dB/div
300 kHz SLOT

h) DEMODULATED
VIDEO SIGNAL
10 mv/div
10 ns/div

Fig. 50 (Cont'd). Playback of FM recordings, 60-MHz carrier, 33-MHz deviation.

The recordings made with laser diodes were not continuous. Continuous recording is accomplished by illuminating 2 separate polygon mirrors, which requires twice the laser power. The argon laser recorder has substantial optical losses due to the line-selecting prism, the etalon, the light modulator, and the aperture which converts the circular beam to a rectangular format. The rectangular format of the laser diode is quite efficient for the illumination of a polygon scanner. A significant source of light loss for the argon laser is the aperture which controls track width. To double the track width, the aperture must be cut in half. To maintain the same exposure over the larger spot, the laser power must be increased 4:1.

The spot size increases linearly with laser wavelength, resulting in lower MTF response for longer wavelengths. However, proportional gain in depth of focus is a benefit of a longer wavelength. Because of the increased laser efficiency and optical efficiency afforded by laser diode systems, enormous savings can be made in weight, size, power, and potentially in cost.

SECTION V

TRADEOFF STUDIES

A. OPERATION BETWEEN 77°K AND ROOM TEMPERATURE

The prospects for building high resolution recorders that use a laser diode operating much above the temperature of liquid nitrogen are not good for the near future. Diode fabrication experts at RCA Laboratories at Princeton, N.J. have indicated that the principal problem is the joint requirement for a continuous output in the 5 to 10 mW range and a wavelength shorter than 720 nm. Figure 51 indicates the drastic reduction of external quantum efficiency with wavelength at two different temperatures[3]. (This data was gathered on pulsed units. The CW diode samples measured had less than 10% efficiency at 77°K at 710 nm). Figure 52 indicates the reduction of power efficiency with wavelength and temperature. From these curves and from laboratory results from 77°-K and 300°-K CW diodes, it is estimated that in order to attain 5-mW CW output at 200°K, a temperature that can be maintained by thermoelectric cooling systems, the laser wavelength would have to be above 760 nm. This is well beyond the sensitivity range of present high resolution films.

Present diode samples have just sufficient light to record continuously (dual hexagon operation) at a velocity of 63,500 cm/s. Small shifts in threshold (30 to 50 mA) due to thermal conductivity changes at the diode/dewar interface can reduce the power output at maximum current to below that needed to record. Figure 53 indicates a shift in diode threshold of 25 mA for a 10°-K rise in diode temperature. The data was taken with a broad area contact diode of set #1. If applied to the diodes of set 3, which lase between 400 and 450 mA and have a 550 mA current limit, lasing action would cease at 125°K at 550 mA.

One of the set #2 diodes was tested of 0°C. These diodes had longer wavelengths (less aluminum) and, therefore, much higher quantum efficiency at room temperature than the other diodes (see Figs. 54 and also 51). Fig. 55 shows the characteristics curve of this diode at room temperature where its wavelength is 800 nm. Slightly less than 1 mW of laser power is available.

A high resolution recorder utilizing a laser diode operating at 200°K or even room temperature requires the development of a high resolution film with suitable sensitivity in the 720-nm to 820-nm wavelength range. Low to moderate resolution films are presently available in this wavelength range and would be suitable primarily for image recording (see Section 5B).

Three possible techniques for cooling laser diodes are available. Thermo-electric coolers are capable of handling a 10- W load at a temperature of 200°K. The input power requirement is 2000 W. Mechanical cryogenic refrigerators are capable of operation down to 77°K. The Displex Model CS-1003 (Air Products and Chemicals, Inc.) is capable of a 1- W load at 77°K. Liquid nitrogen dewars equiped with

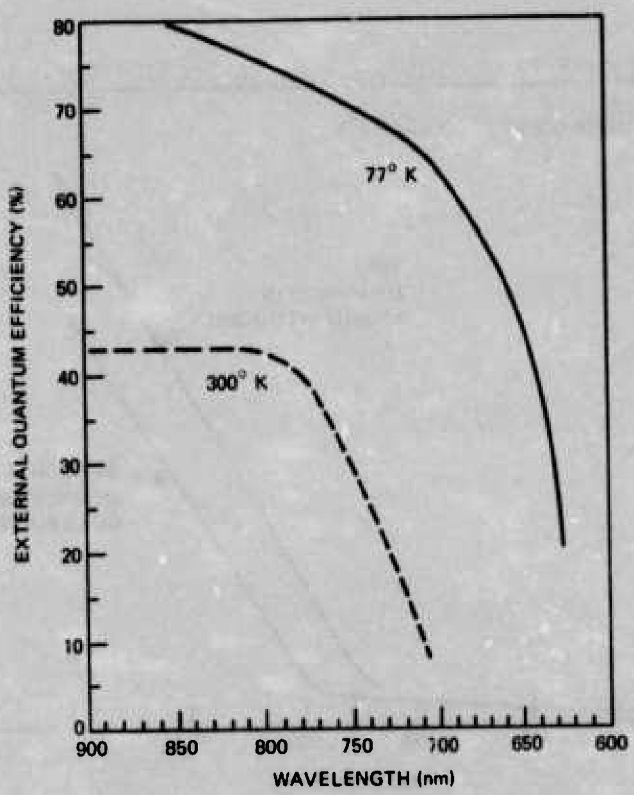


Fig. 51. Dependence of external quantum efficiency with wavelength and temperature.

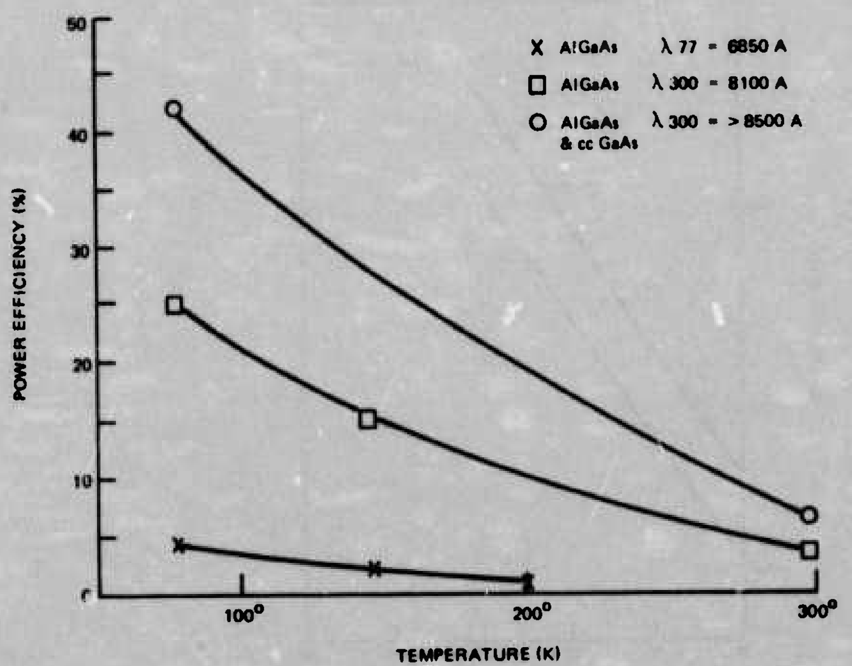


Fig. 52. Dependence of power efficiency with wavelength and temperature.

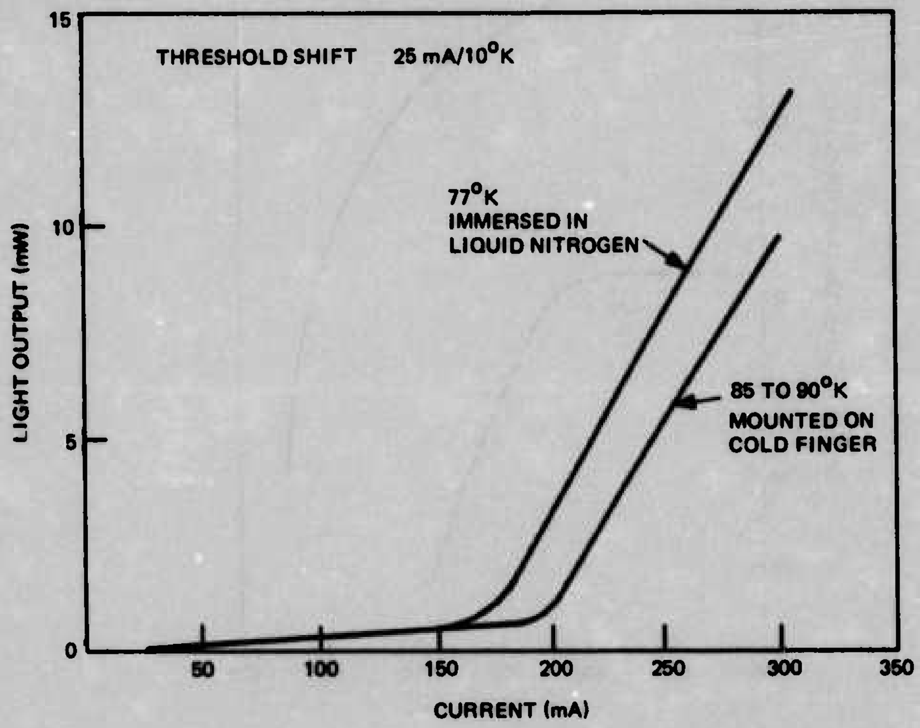


Fig. 53. Threshold shift with diode temperature.

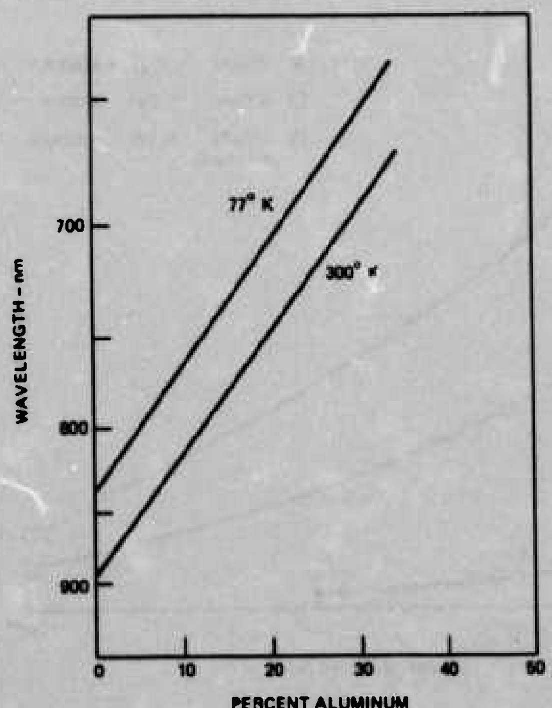


Fig. 54. Effect of aluminum concentration and temperature on emission wavelength.

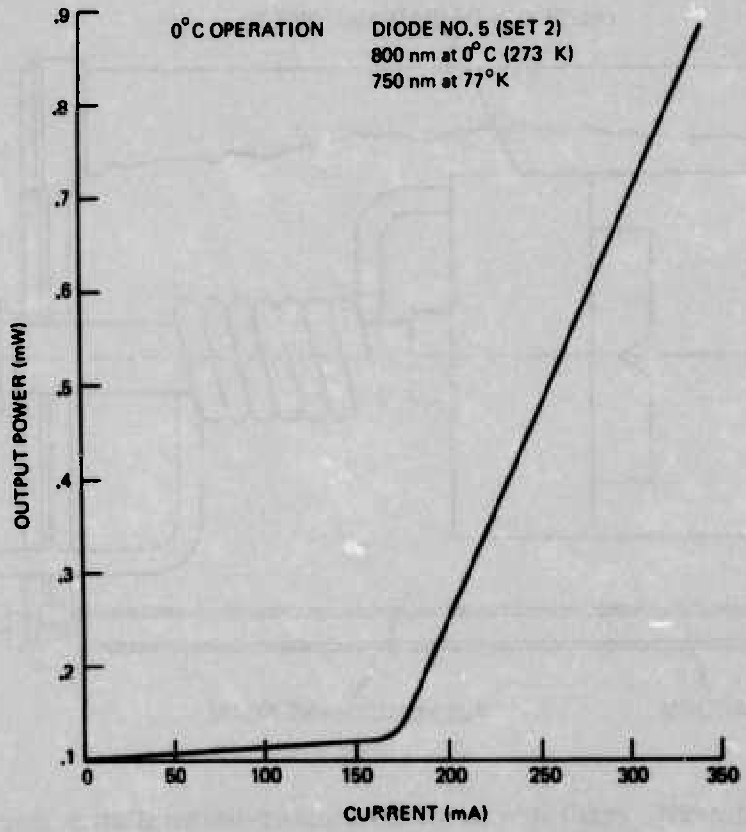


Fig. 55. O^{O}C operation of a set #2 diode.

automatic refill systems are easily capable of tens of watts of load at 77^{O}K. Figure 56 shows an automatic refill dewar built by RCA for a helicopter-borne laser diode illuminator.

B. ROOM TEMPERATURE OPERATION

Stripe geometry laser diodes capable of room temperature operation have recently been developed by RCA Laboratories. These diodes emit 5 to 10 mW of continuous power at a wavelength of 800 nm. Readily available Kodak films sensitive to this wavelength are 2424, 2481 and HIE-135. The emulsions of all three films are essentially the same. The spectral response is very broad (350 to 950 nm) and the sensitivity is high (.10 erg/cm^2 for D=1). These films are capable of 50% MTF at 25 cycles/mm. The granularity and resolution are not suitable for recording the wideband signal considered in this program. However, room temperature diodes could be used with these IR films in moderate resolution image recording equipment. Special-order Kodak infrared films, such as Spectroscopic IV-N, have improved granularity and resolution and could be used in a moderate resolution signal recorder. These films were not tested during this program.

Test recordings of a 5-MHz tone were made on HIE-135. After appropriate adjustment of development parameters, good recordings were achieved. Fig. 57a shows the 5-MHz tone (6 cycle/mm) with a track width of 30-35 μm. Fig. 57b is the

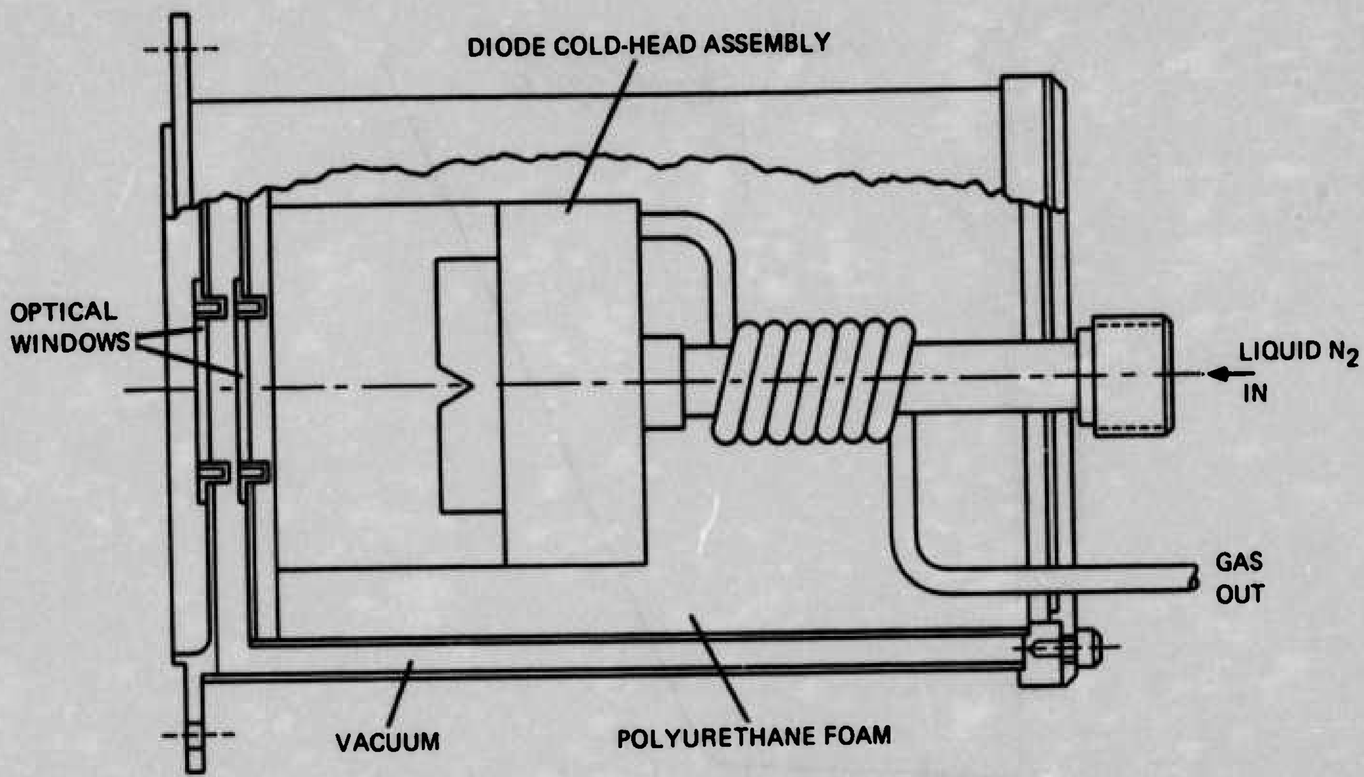


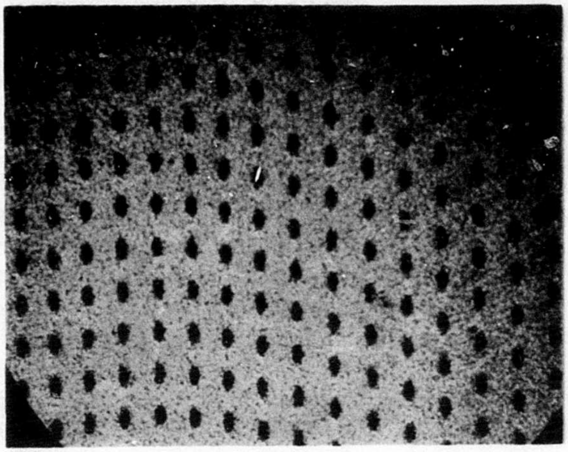
Fig. 56. Automatic refill dewar for helicopter-borne illuminator.

same film at 200 X magnification and Fig. 57 c is a 100-cycle/mm tone on AGFA 10E75 (25-mm track width) also at 200 X magnification. The effect of the granularity of the high speed IR film on the quality of the playback signal was not investigated.

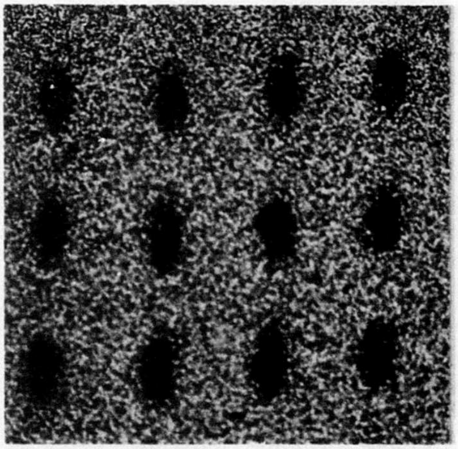
C. TESTS WITH KODAK SO-173 HIGH RESOLUTION EXTENDED RED FILM

A brief series of record tests were made using Kodak SO-173 high resolution extended red film. Initial recordings exhibited faintly detectable modulation and high base fog levels when exposed and developed in the same manner as AGFA 10E75. Experiments with exposure and developing time (Prostar 63 °F) improved base fog to an acceptable level but contrast remained low. It appears that the film was adequately exposed but underdeveloped. Increasing development time above present periods will increase the base fog to an unacceptable level, using Prostar at present concentrations and temperatures. A radically different development process or a new developer is required.

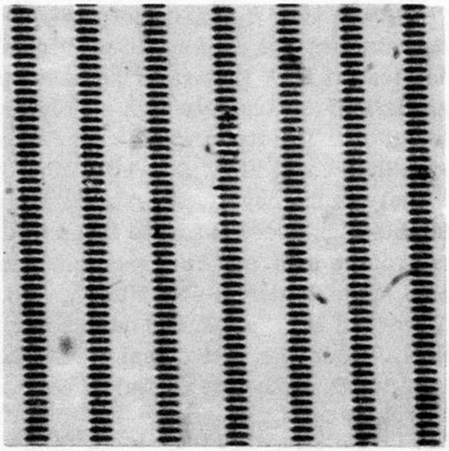
Discussions with Kodak indicated that an anti-halation undercoat (similar to that used in type 5460 film) may be required for high contrast recordings. Other silver solvent development chemistry was suggested as an alternative to Prostar. The possibility also exists that there may be a reciprocity problem with this emulsion whereby significant density cannot be achieved at very short exposure times.



a. A 5-MHz recording on High Speed Infrared Film (HIE-135) MAG = 75X



b. 6 cyc/mm recording, High Speed Infrared MAG = 200X (35-μm track)



c. 100 cyc/mm recording, high resolution extended red MAG = 200X (25-μm track)

Fig. 57 Granularity comparison of IR film with high resolution extended red film.

SECTION VI

CONCLUSIONS AND RECOMMENDATIONS

This investigation has shown that laser diodes have the potential to provide superior performance over conventional laser techniques when used in a laser recorder. Their internal modulation capability along with their small size, weight, and power requirement should significantly increase the use of laser film recording systems. These features should significantly reduce the cost as well as input performance and reliability of film recording systems.

The developmental injection lasers used on the program were internally modulated from 1-200 MHz (± 2dB), and film recordings of signal frequencies in excess of 100 MHz (160 cycles/mm) have been made. Still-scan playback of a 30 MHz FM tone was performed. A signal-to-noise ratio of 31 dB p-p/rms over a 30 MHz bandwidth was achieved. The output power and beam distribution was sufficient to allow continuous recording at 63,500 cm/s (25,000 in/s).

It was shown that stripe geometry, double heterojunction (Al Ga)As lasers can provide 5 to 10 mW of CW power at 710 nm when cooled to 77°K. Recently developed room temperature diodes can provide similar power at 800 nm wavelengths. Samples under test at RCA Laboratories have been operating several thousand hours with no degradation. Extremely high resolution films (2000 cyc/mm) are not presently available with sensitivity to wavelengths beyond 720 nm. Improvements in (Al Ga) As diodes that would allow 5 to 10 mW at 200° K at wavelengths shorter than 720 nm are not likely in the near future. A finer grain, high resolution version of presently available high speed infrared films would allow wideband signal recording with room temperature lasers. At present, wideband signal recording appears restricted to cooled laser diodes (below 100°K). However image recording at 25-MHz rates (50% record MTF at 92,000 cm/sec) appears quite feasible with room temperature lasers. Moderate rate signal recording suitable for optical processing also appears feasible with room temperature lasers.

Fig. 58 shows a block diagram of a 30-MHz FM signal recorder using a laser diode cooled to 77°K. An automatic refill dewar system is shown which will maintain the coolant level. The fill cycle is controlled by two resistance thermometers located in the dewar at the desired maximum and minimum levels. An exposure control, consisting of a variable reflectivity mirror, will allow the average record power to be set independently of laser bias. The laser can then be biased for minimum harmonic distortion. Timebase correction is not shown but techniques are discussed in references 5 and 7.

The laser diode used in the signal recorder is a stripe contact, double heterojunction device. Its emission wavelength is 720 nm (or less) with a peak output power of 8 to 10 mW. A 4 to 5 mW average power is required. Continuous recordings

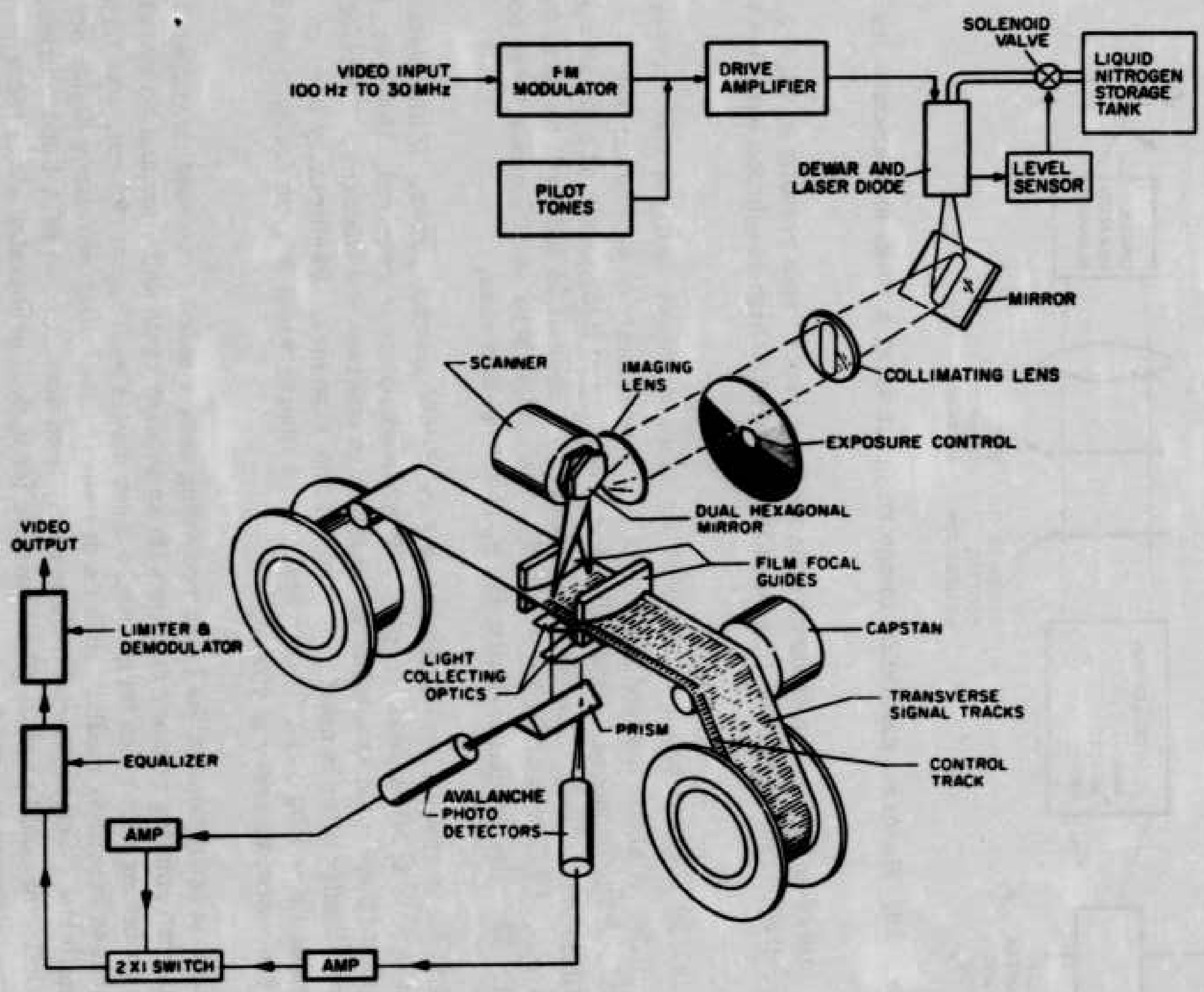


Fig. 58. Diagram of laser diode FM signal recorder.

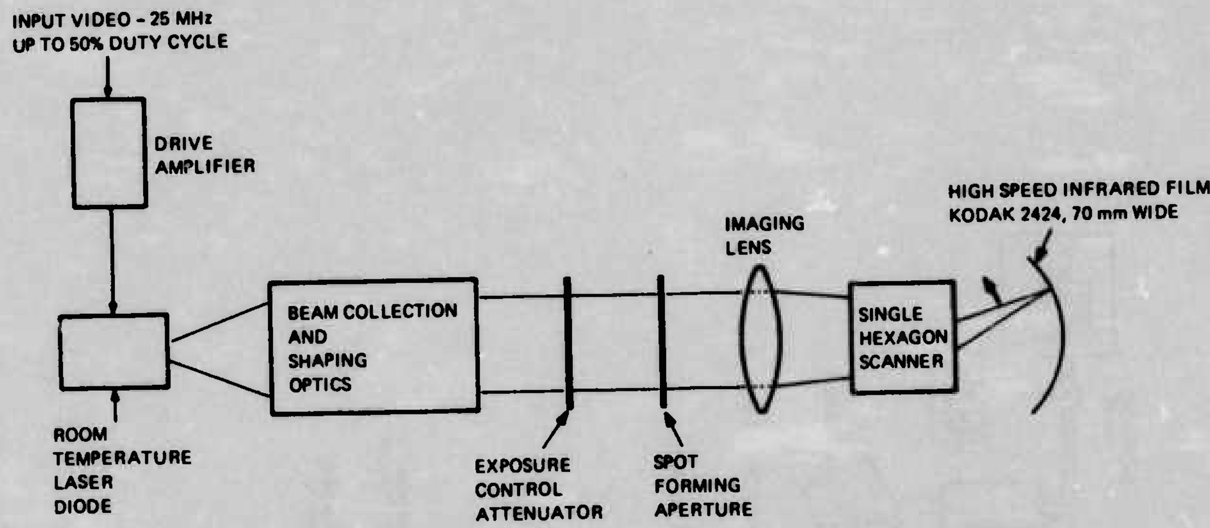


Fig. 59. Moderate resolution image recorder using a room temperature diode.

are achieved using the dual hexagon scanner and a record spot velocity of 63,500 cm/sec (25,000 in/sec). The film used is AGFA 10E75 high resolution extended red film.

Fig. 59 shows a block diagram of an image recorder using a room temperature laser diode. A single hexagon scanner with a spot velocity of 92,000 cm/sec (36,000 in/s) is proposed. This will allow recording of information at a 25-MHz rate (50 million pixels/sec). The recorded spatial frequency of 25 MHz will be 25 to 30 cycles/mm at which the film MTF is 50%. The optical MTF is 90% under these conditions. The film resolution limits the pixel rate in this case.

The laser is assumed to be capable of 5 to 10-mW average power. If high speed IR film (Kodak 2424) is used, roughly .10 mW peak power is required. However, the diode must be operated as a laser to achieve high contrast and linearity. Therefore, a neutral density filter is used to set the average exposure. Preliminary tests on samples of a new film (SO-289) indicate a 3 to 1 improvement in granularity is available for an equivalent increase in power.

Future investigations in the laser recording area should be directed towards: 1.) replacing the rotating scanner mirror with an acousto-optic deflector, and 2.) investigating recording with room temperature laser diodes emitting at 820 nm, and 3.) using a rapid access recording medium such as dry silver film. High efficiency deflectors of paratellurite (TeO_2) material have recently been developed at RCA Laboratories. Such a deflector could produce films suitable for optical processing since track displacement due to mirror facet errors would no longer be a problem. Room temperature lasers have recently been developed at RCA labs that emit 5 to 10 mW at 800 nm and in excess of 30 mW at 820 nm. Kodak SO-289 fine grain infrared film is compatible with these wavelengths and has the resolution required for a high quality image recorder. A solid state laser signal recorder employing a room temperature

laser, an acousto optic deflector, and SO-289 film could provide film recordings suitable for optical processing. A similar recorder could also be capable of recording TV-rate imagery directly onto film. The use of an easily processed, inexpensive rapid access recording medium would significantly increase the attractiveness of the laser film recording system in printers and in many image and data storage applications that currently rely upon magnetic recorders.

APPENDIX A

LIGHT COLLECTION FROM SEMICONDUCTOR LIGHT SOURCES OF VARIOUS BEAM PATTERNS

Two types of semiconductor light sources are generally available: the light emitting diode (LED) and the laser diode. The first source tends to produce a circular (axially symmetric) beam while the second source tends to produce a rectangular beam. The laser diode operates as an LED when the current is reduced below lasing threshold. The task is to find the power collected by a given lens from a source of a known beam pattern.

1. Power in a Circular Cone - LED

Assume that the beam intensity of the source can be described by:

$$J(\theta) = J_o \cos^n \theta \tag{1}$$

where $J(\theta)$ = radiant intensity (W/Sr) of the source at an angle θ with respect to the optical axis (half angle of the cone).

J_o = maximum intensity (on axis)

Source radiance is defined by:

$$N = \frac{J(\theta)}{\cos\theta \, dA} \tag{2}$$

where: N = radiance ($w^{(2)}/cm^2$ steradian)

dA = elemental source area

To find the power radiated into a cone of half angle θ, spherical coordinates can be used where the elemental area (dS) on the surface of the sphere is given by:

$$dS = r^2 \sin\theta \, d\theta \, d\phi \tag{3}$$

Using a sphere of unit radius this becomes,

$$dS = \sin\theta \, d\theta \, d\phi \tag{4}$$

Having the radiant intensity (I) in watts per sterdian, integrating over the total number of steradians intercepted by a given lens will give the power in watts intercepted by that lens. Therefore, the power $P(\theta)$ present within a cone of half angle θ is:

$$P(\theta) = \int_0^{\theta}\int_0^{2\pi} J_o \cos^n\theta \sin\theta \, d\theta \, d\phi \tag{5}$$

$$= 2\pi J_o \int_o \cos^n\theta \sin\theta \, d\theta$$

letting $u = \cos\theta$

$du = -\sin\theta \, d\theta$

$$\int \mu^n dn = \left(\frac{1}{n+1}\right) \mu^{n+1}$$

Therefore,

$$P(\theta) = -2\pi J_o \frac{(\cos\theta)^{n+1}}{n+1}$$

Rearranging

$$P(\theta) = \frac{2\pi J_o}{n+1}\left[1 - \cos^{n+1}\theta\right] \tag{6}$$

<u>Example</u>

Assume a beam measure 32^o full angle to the half intensity points ($\theta = 16^o$). Find the power collected by an f/2 lens.

$$J_\theta = J_o \cos^n\theta$$

$$\text{since } \frac{J\theta}{J_o} = \frac{1}{2}$$

$$\frac{1}{2} = (\cos 16^o)^n$$

$$\log \frac{1}{2} = n \text{ los } \cos 16^{o}$$

$$n = \frac{\log \frac{1}{2}}{\log \cos 16^{o}}$$

$$n = 17.5$$

$$J_{\theta} = J_{o} \cos^{17.5}\theta$$

The power contained in the cone within the angle θ is:

$$P\theta = \frac{2\pi J_{o}}{18.5} \left[1 - \cos^{18.5}\theta\right]$$

Since J_o is not always easily measured, we can set $J_o = 1$ and find the fraction of the total power within the cone of half angle θ. The total power emitted into a hemisphere ($\theta = 90^o$):

$$P\,(90^{o}) = \frac{2\pi}{18.5} \left[1 - \left(\cos 90^{o}\right)^{18.5}\right]$$

$$= .3396$$

For an f/2 lens, θ is given by:

$$\theta = \arcsin \left(\frac{1}{2\,(f/\#)}\right)$$

$$= 14.5^{o}$$

Therefore,

$$P\,(\theta) = \frac{2\pi}{12.1} \left[1 - \left(\cos 14.5^{o}\right)^{12.1}\right]$$

$$= .1683$$

% of total power collected by f/2 lens is:

$$\frac{.1683}{.3396} \times 100 = 49.6\%$$

2. Power in a Rectangular Cone - Laser Diode

Assume $J(\theta) = J(\theta_x, \theta_y) = J_o \cos^n \theta_x \cos^m \theta y$ (7)

$$N = \frac{J(\theta)}{\cos\theta \, dA} \qquad N = \text{source radiance}\left(\frac{\text{watts}}{\text{cm}^2 - \text{steradian}}\right)$$

The power through an elemental area is:

$$dP = N(\cos\theta \, dA)\, d\Omega = J(\theta)\, d\Omega \tag{8}$$

The elemental solid angle is:

$$d\Omega = r^2 \, d\theta_x \, d\theta_y$$

Substituting Eq. 7 and Eq. 9 into Eq. 8

$$dP = J_o \cos^n \theta x \cos^m \theta_y \, d\theta_x \, d\theta_y$$

Integrating

$$P(\theta) = J_o \int_{\theta_x} \cos^n \theta_x \, d\theta_x \int_{\theta_y} \cos^m \theta_y \, d\theta_y \tag{10}$$

These integrals can be evaluated separately by graphical means in terms of the fraction of the power contained within the angle θ in each direction. To separate the integrals, assume that the integral over θ_x (power in the x direction) is a real number. Since we are dealing with ratios and since the rectangular cone is symmetric in both the X and y directions, integrals need only be taken over angles from 0 to $\pi/2$.

Hence, the ratio of the power collected over a certain portion of the y direction ($\theta_y = \pi/2$) is given by:

$$\frac{P(\theta_{y1})}{P(\theta_y = \frac{\pi}{2})} = \frac{J_o \int^{\pi/2} \cos^n \theta_x \, d\theta_x \int_o^{y1} \cos^m \theta_y \, d\theta_y}{J_o \int^{\pi/2} \cos^n \theta_x \, d\theta_x \int_o^{\pi/2} \cos^m \theta_y \, d\theta_y} \tag{11}$$

$$\frac{P(\theta_{y1})}{P(\theta_y = \pi/2)} = \frac{\int^{\theta_{y1}} \cos^m \theta_y \, d\theta_y}{\int_o^{\pi/2} \cos^m \theta_y \, d\theta_y} = \text{Fraction of power in } y \text{ direction collected by lens} \quad (12)$$

These integrals can be evaluated graphically. A similar procedure is used to evaluate the fraction of the power in the x direction collected by the lens. Multiplying these two fractional results gives the fraction of the total power (emitted into a hemisphere) that is collected by a lens.

$$\text{Fraction of the Total Power collected by lens} = (\text{Fraction in } \theta_x \text{ direction}) \times (\text{Fraction in } \theta_y \text{ direction}) \quad (13)$$

<u>Example</u>

Assume a laser diode has a beam pattern 32^o full angle to half intensity ($\theta_x = 16^o$) and 10^o full angle to the null ($\theta_y = 5^o$). For all practical purposes, an f/2 lens will collect all the light in the θ_y direction. Therefore, the θ_x direction only must be calculated. As calculated in the example of Section A, for $\theta = 16^o$ at half intensity:

$$J(\theta_k) = J_o \cos^{17.5} \theta_x$$

The graphical integration to be performed is then:

$$\int \cos^{17.5} \theta_x \, d\theta_x$$

A plot of $\cos^{17.5} \theta$ is shown in Fig. A-1. The total power is given by:

$$\int_o^{90^o} \cos^{17.5} \theta_x \, d\theta_x = 836 \text{ units}$$

The power collected by an f/2 lens ($\theta = 14.5^o$) is

$$\int_o^{14.5^o} \cos^{17.5} \theta_x \, d\theta_x = 603 \text{ units}$$

The percent of the total power collected by an f/2 lens is:

603/836 X 100 = 72%

FOR A BEAM WITH HALF INTENSITY POINTS AT $\pm 16^{\circ}$, THE INTENSITY CAN BE DESCRIBED BY $J_{\theta} = J_{o} \cos^{17.5}\theta$

$$\frac{1}{2} \text{ TOTAL POWER IN BEAM} = \int_{0}^{90^{\circ}} J_{\theta}\, d\theta$$

$$\frac{1}{2} \text{ POWER COLLECTED BY f/2 LENS} = \int_{0}^{14.5^{\circ}} J_{\theta}\, d\theta$$

% POWER COLLECTED BY f/2 LENS

$$\frac{\int_{0}^{14.5^{\circ}} J\theta\, d\theta}{\int_{0}^{90^{\circ}} J\theta\, d\theta} = \frac{603 \text{ UNITS}}{836 \text{ UNITS}} \Longrightarrow 72\%$$

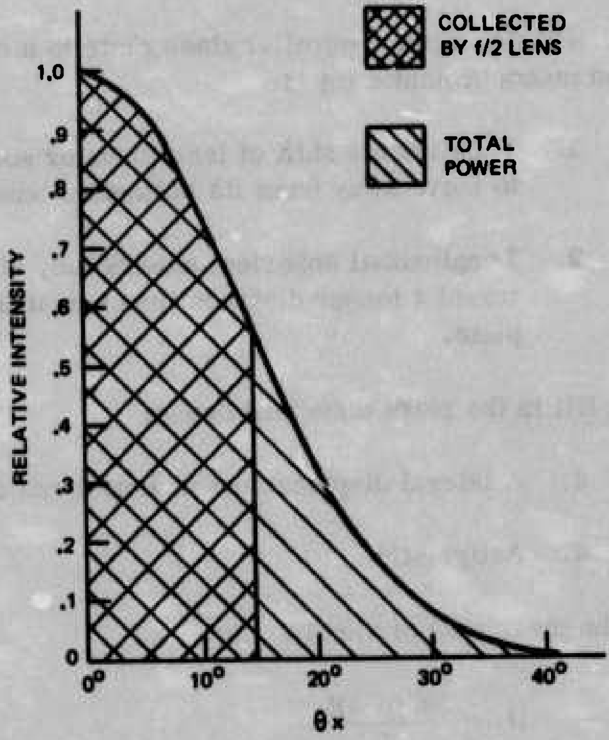


Fig. A-1. Plot of $\cos^{17.5}\theta$ for graphical integration.

APPENDIX B

EFFECT OF GLASS WINDOW ON CONVERGING OR DIVERGING BEAM

Placing a plane parallel glass plate in a converging or diverging beam has two effects on monochromatic light:

1. Longitudinal shift of lens focus or source (laser diode) position. (Diode appears to move away from its collection lens.)

2. Longitudinal spherical aberration, since the ray at the edge of the beam has to travel a longer distance than one at the center which is normal to the glass plate.

A tilt in the glass plate will cause:

3. A lateral displacement of lens focus or source (laser diode) position.

4. Astigmatism.

The magnitude of effect #1 is:

$$D = \frac{n\,(n-1)t}{n}$$

where:

D = displacement

t = glass plate thickness (1)

n = index of refraction of the glass

The magnitude of effect #2 is:

$$OPD = \frac{t}{n}\left[1 - \frac{n\cos}{\sqrt{n^2\,\sin^2\theta}}\right]$$

where:

OPD = optical path difference between edge ray and center ray. (2)

θ = half angle of converging/diverging cone.

n = index of refraction of the glass

The value obtained from the above equation should be compared to the allowable depth of focus from the Rayleigh criteria (OPD = $\lambda/4$):

$$\text{Depth of focus} = \pm 2\ \lambda(f/\#)^2 \tag{3}$$

Optical path difference between the center ray and edge ray of a lens forming the cone will cause center (paraxial) ray and edge rays to focus at two different points. This will affect the energy difference in the Airy disc pattern of the focused spot as follows:

	Energy in Disc	Energy in Rings
Perfect lens (OPD = 0)	84%	16%
1/4 Rayleigh limit (OPD = $\lambda/16$)	83%	17%
1/2 Rayleigh limit (OPD = $\lambda/8$)	80%	20%
1 Rayleigh limit (OPD = $\lambda/4$)	68%	32%

The effect of one wavelength of optical path difference (4 times Rayleigh limit) on MTF is shown in Fig. B-1.

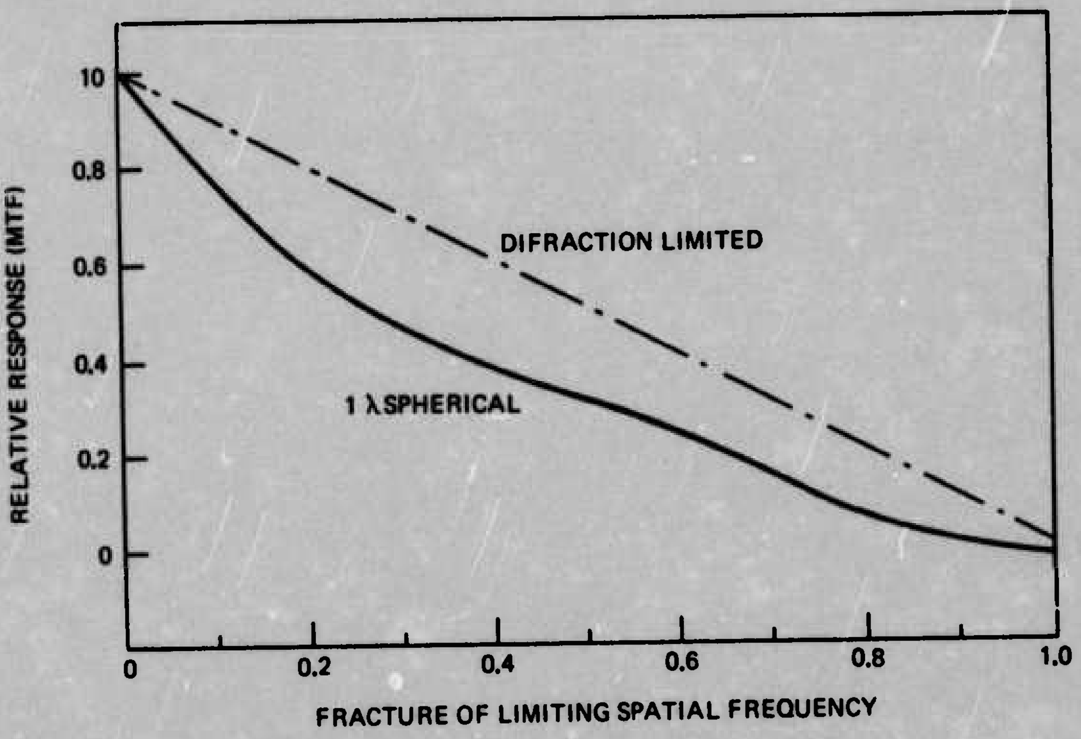


Fig. B-1. Effect of spherical aberration on MTF

It can be seen that wavefront distortion or optical path difference can cause a degradation in record/play response. For the laser diode system, only 1-inch of the 2-inch along-track beam is intercepted by the mirror facet. For the f/2 collection lens, this corresponds to a half angle of 7.8^{o}. Therefore, from Eq. 2 using a 2-mm window thickness:

$$\text{OPD} = 6.7\ \mu\text{m}$$

Since this light is coming from different portions of an f/2, cone the worse case depth of focus is given by Eq. 3 using f/2:

$$\text{Depth of focus} = \pm\ 11.4\ \mu\text{m}$$

Therefore, the optical path difference is about half the Rayleigh criterion or $\lambda/8$.

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