AREA B

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STORAGE DEVICES—THEIR POTENTIAL AND RELIABILITY

Part I

LASER INFORMATION RECORDING SYSTEMS
A Survey

By

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Since its advent, the laser and its unique properties have been the subject of intense scientific and engineering activity. Each advance has generated expanded interest and activity in a diverse series of applications. A major application of interest, that of recording information, is in advanced system exploration stages.

What properties of the laser give it a pre-eminent position in advanced information recording systems R & D?

What types of systems are being developed?

What are the current limitations in recording system applications?

What rate of progress is being made to overcome these?

What advances could be expected to develop alternate systems approaches?

Five important characteristics of the laser as a radiant energy source for information recording systems design are:

(1) High power density output
(2) High degree of collimation (low divergence)
(3) Monochromatic output
(4) Plane polarized output
(5) Coherency

The first three characteristics permit achieving excellent resolution, the second, third, and fourth permit use of a variety of devices for modulation and deflection, while the fifth has opened new approaches to high density storage via holography. Taken in total, these characteristics promise high information packing density and high speed recording in systems applications. Potential densities of 12μ/character (1μ spot size) and rates of 100,000 characters/sec. are feasible compared to 100μ/character (5-10μ spot size) and 60,000 characters/sec. electron beam recording rates.

Prior to the advent of the laser, the only high output, radiant energy sources were isotropic radiators, i.e. tungsten wires, carbon arcs, etc. The output energy of an isotropic source is omnidirectional and is distributed according to a physical law over a wide range of wavelengths while detectors (recording media) normally respond to relatively narrow bandwidths. In a practical sense, this means that these sources had to be operated at very high temperatures to obtain even marginal power outputs in a narrow spectral range corresponding to the detector absorption. For example, to achieve the energy density per unit of time in a one angstrom bandwidth attainable from a one milliwatt laser focused to a two millimeter diameter spot would require an incandescent source to be operated at 10^7 degrees Kelvin. Such temperatures are found only in stellar interiors. Operation of isotropic sources at very high temperatures results in short source life. In addition, since radiation from these sources is highly divergent - emitted in all directions - complex lens and reflector optical systems are required to focus the light, resulting in a considerable power loss.

The laser generates light throughout a large volume in a unique way that allows the emitted light to be focused with a simple lens system to a small spot - as small as tenths of a micron (1 micron =0.04 mil). A laser beam can be focused readily to achieve a power density of 10^{15} w/cm^2 in a 10μ spot for a pulse duration of 10 nanoseconds.[1] For comparison, the radiated power at the sun's surface is about 10^5 s/cm^2. Laser outputs in the kilowatt range are easily attainable for times longer than a millisecond. For our purposes, we will be concerned with CW (continuous wave) lasers. These give outputs in the milliwatt to 1 watt range over a single or very narrow wavelength range. Consequently, for a matched detector (recording medium), one has power densities in a narrow spectral range at least thousands of times greater than from previous radiant energy sources. There are many unusual imaging materials which can give extremely sharp images, but which are low in sensitivity limiting their usefulness. The great intensity of the laser means that many of these materials can be explored since extremely short exposures may be combined with high reduction ratios and rapid access permitting storing and retrieving large amounts of information from a small area.

As mentioned above, the monochromaticity of laser light is exceptional - the light has nearly a single wavelength or frequency. Ordinary light has colors or wavelengths ranging through the spectrum from the blue to the red regions. A major problem in lens design is selecting glasses of different refracting powers and shaping the lens surfaces to focus all the different wavelengths of the light. With laser light, these considerations no longer apply and the optical system is simplified. The emitted laser light beam has a single direction and does not diverge like ordinary light so field lenses are not needed to confine the beam.

[1] C.G. Young et al, "Optical Avalanche Laser", Journal of Applied Physics, 4319-24, 37 (1966)

One of the more important characteristics of laser light is that it can be obtained plane polarized. Electromagnetic radiation, which includes normal light, vibrates perpendicular to the direction of light beam propagation, but in all possible directions. Plane polarized light vibrates in only one direction. In the laser, emissions are stimulated by means of reflection at the end mirror in the laser assembly and only light polarized in one plane is produced. This property is very important in recording system design, i.e. modulation, and for some systems, also deflection.

The coherency characteristic of laser light means that unlike normal light, laser radiation comes out in a single train of waves rather than a superposition of many waves incoherently spaced at random. These waves can be controlled and shaped accurately to give images sharper than those obtained with ordinary light. This characteristic permits holographic recording.

Laser action can be achieved in a variety of materials in different states of matter.

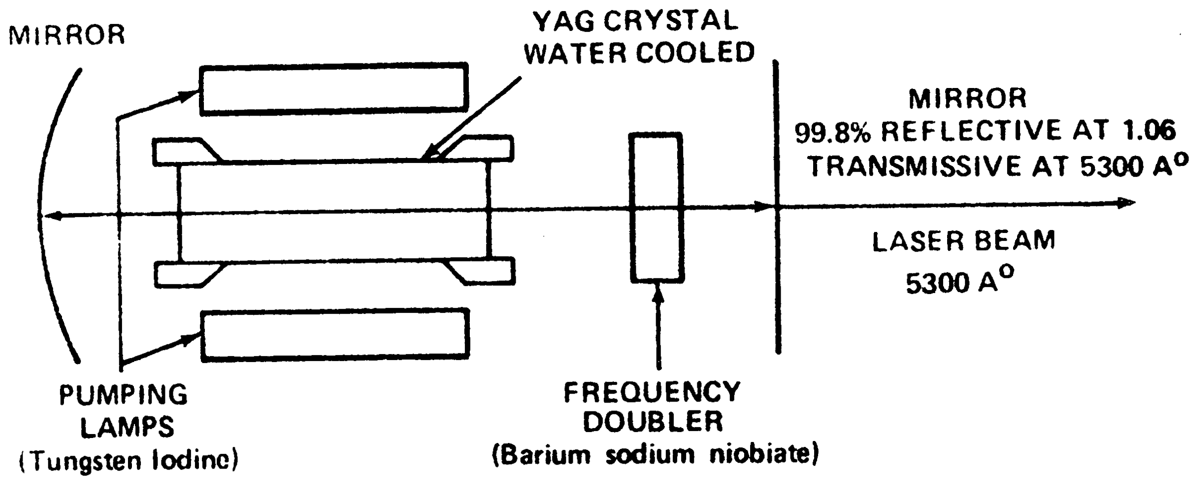
(1) Solid
(2) Gas
(3) Liquid
(4) Junction (semiconductor)

In solid and liquid lasing materials, certain ions located as "impurities" in the material are the active radiators. In the original ruby laser, a sprinkling of chromium ions (Cr^{+++}) distributed in an aluminum oxide crystal lattice operate as the emitters. In other solid and certain liquid lasers, various rare-earth ions are incorporated for the same role. In gas-discharge lasers, the active role may be played by certain atoms, ions, or by simple inorganic molecules, such as carbon dioxide. In semiconductor junction lasers, the crystal lattice of the host material itself has a primary role along with that of the "impurities" in the light emitting process.

TABLE I.

CONTINUOUS WAVE LASERS

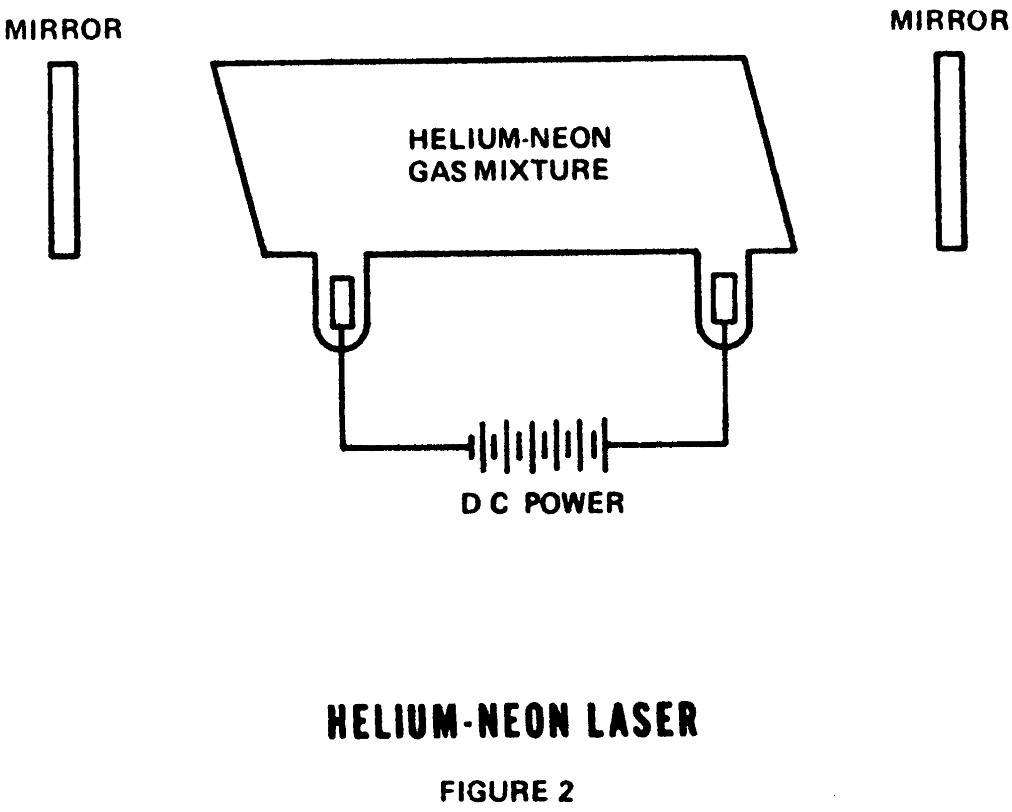
LASER	PUMP	INPUT POWER	OUTPUT POWER	OUTPUT WAVELENGTH
YAG RoD	Sodium in Mercury vapor discharge lamp	1 KW	20-30W	1.04μ
YAG RoD 3 cm long 0.5 cm diameter	Tungsten Filament	1.7 KW	20W	1.34μ
		1.7 KW	27W	1.06μ
		1.7 KW	.04W	.67μ
		1.5 KW	1/8W	.53μ
Carbon Dioxide-nitrogen-helium gas	Direct discharge through tube, D.C. or A. C.	10 KW	1KW	10.6μ
Carbon Dioxide-nitrogen-helium gas tube length: 1.8m (~6 ft.) diameters: 2.5-10cm (~1-4 in.) (water cooling required for continuous operation)	Direct discharge through tube, A.C. or D.C.	2 KW	150W	10.6μ
Helium-neon gas 12" x 8" x 5" Tube lifetime: over 5,000 hrs.	Direct discharge D.C.	10-20 W	1.5-1MW	0.632μ
Krypton-Argon	Direct discharge 60 cycle A.C.	1 KW	300MW	0.5145μ
			500MW	0.488μ
Krypton	Direct discharge	1-2KW	1.5-0.3W	0.4762μ, 0.5208μ 0.5682μ 0.6471μ
Argon	Direct discharge	1-2KW	1.0-0.1W	0.4579μ, 0.4765μ, 0.4880μ, 0.4965μ 0.5017μ, 0.5145μ



CW YAG LASER

1/8W OUTPUT AT 5300 A°
FOR 1500 W PUMPING POWER

FIGURE 1



HELIUM-NEON LASER

FIGURE 2

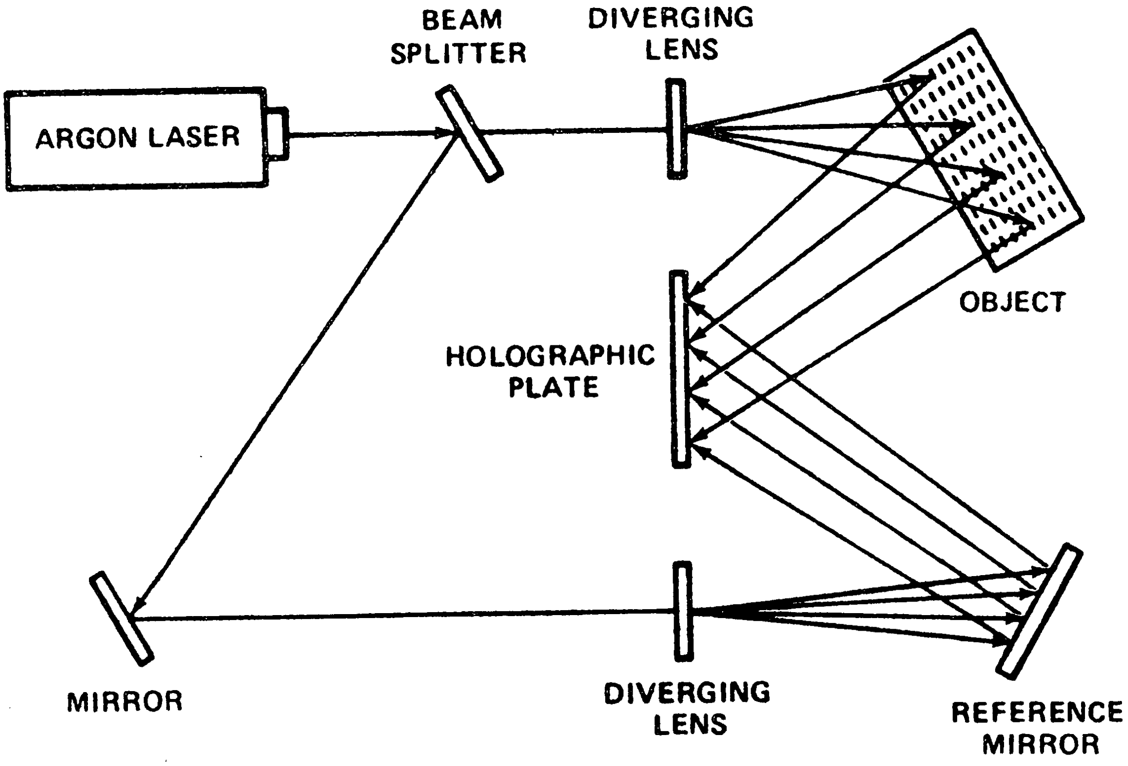
Typical solid materials besides ruby which may be used are glasses containing neodymium ions (Nd^{+++}), "YAG", or containing a variety of rare-earth ions, "alphabet YAG", or a calcium phosphate containing neodymium, "FAP". Although ruby, the first laser, required a very high power, pulsed, flash lamp to achieve laser oscillations, later developed materials YAG and FAP, can oscillate continuously using a tungsten filament source as the "pump". Table 1 lists typical continuous wave lasers which have been used as sources in laser information recording systems. The lasers with outputs in the visible spectrum (0.5 - 0.6μ) have been used to record on wavelength sensitive media, i.e. silver halide emulsions, Dry Silver films, while the lasers with outputs in the infrared (1.0μ - 10μ) have been used to record via thermal effects, i.e., heating or evaporating a metal film, burning a hole in a film. Figure 1 is a schematic of a YAG laser, while Figure 2 is a schematic of a helium neon gas laser.

The laser has been used in two modes to achieve information recording:

(1) Holography
(2) Direct writing

HOLOGRAPHIC - DIGITAL MEMORY SYSTEMS

In holography, a laser beam is split into an object beam which shines on the object, and a reference beam which shines directly on a recording film. Light reflected from an object when combined with light from a reference source forms an interference pattern on a film, Figure 3. The resulting interference pattern bears no resemblance to the object. When the film is developed and the beam of a laser is passed through it, the object is reconstructed in three dimensions at a focal point. Ordinary photography using lenses records only the intensity of the light (the variations in brightness) reflected from an object.



HOLOGRAPHIC RECORDING

FIGURE 3

Holography, which does not employ a lens, records both wave patterns and intensity patterns. When light strikes a point on an object, it is reflected back from the point in ever increasing concentric rings -- like the rings of waves caused by a pebble dropped into a pool. A complex object has innumerable reflection points so that a large number of sets of wave rings are reflected. Taken all together, these reflections make up an extremely complex pattern that is distinctive to the object being illuminated. While holographic principles have been known for two decades, the laser provides the intense source of coherent light needed to stimulate renewed interest in applications.

A hologram for information storage purposes is a record of a three-dimensional, stationary, interference pattern in a photosensitive material. A typical, thin, silver halide emulsion stores only a "fringe system" that is essentially a cross-section of the interference pattern. If the holograph is recorded in a material much thicker than the average fringe spacing of the pattern, it can be considered a "volume" hologram. The volume hologram has redundancy in that it is equivalent to a large number of thin holograms of the same interference pattern. There is no fundamental difference between the recording of a thin (surface) hologram and a volume hologram. Differences do appear when one wishes the series of thin holograms in a volume hologram to represent a corresponding series of different objects. In doing this, one is seeking to increase the capacity to store information. A volume hologram is "readable" only from a very narrow angular interval. Outside this range, the image intensity is very low. A series of superimposed holograms can be recorded and read-out by operating at selected rotational increments larger than the "read-out" angle interval for a volume hologram. Typically, the discrimination interval in an alkali halide crystal can be 0.1° permitting successive holograms to be recorded and read out at 0.2° or larger increments.

A variety of techniques are being explored seeking to exploit holography as a basis for high density, digital data memory systems.

(1) Multiple exposure holograms in which different objects are exposed separately with the same reference beam at different angles.[1]

(2) Multiple exposure holograms in which the reference beam and the element are changed.[2] The reference beam is part of the code by which objects are retrieved.

(3) Multiple exposure holograms in which the reference beam is changed and coded by changing the position of a ground glass plate between exposures.[3]

The interference patterns are diffused over the entirety of the recording medium. The thicker the recording medium, the greater the number of images that can be stored in it. For maximum usefulness, the number of superimposed images should be large. However, each succeeding image will reduce the resolution of those preceeding. In the limit, the number of holograms that can be recorded on a single plate is limited by the required resolution and the finite information limit of the recording medium. It is interesting to note that the latter is also a major limiting factor in integral imaging.

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[1] G. W. Strike, F. H. Westerveldt, R. G. Zech, Proc. I.E.E.E. <u>55</u>, 109 (1967)

[2] M. Marchant, D. Knight, Optica Acta, <u>14</u>, 199 (1967)

[3] R. J. Collier, K. S. Pennington, Appl. Opt. <u>6</u>, 1091 (1967)

Volume holography places severe requirements on the recording material.

(1) Extremely high resolution
(2) High dimensional stability
(3) Low grain noise
(4) Good optical quality

In addition to special silver halide photographic emulsions, a number of photochromic[1] and alkali halide crystals have been used in exploring this technique. The imaging mechanism in the latter materials is based on various color center transitions. Some of their properties of major interest are:

(1) Very high resolution
(2) Reversible transitions permit erasing and revision
(3) The transitions are nearly instantaneous and require no development

Use of a dichromated gelatin holographic plate, which has the advantage of reducing the laser beam power required for retrieval by a factor of 20, has been reported by Bell Laboratories personnel.[2] This means that on "read-out" as much as 96% of the reconstructing beam power passes through the hologram to the detector array. Previous recording materials permitted less than 6% of the reconstructing beam power to illuminate the detector array. In the recording technique, a dichromated gelatin film is exposed using an argon laser beam and developed by gently agitating it in water. Following this, it is rinsed in isopropanol or some other aqeous solvent and air dried. It is then coated with a lacquer and air dried. Present techniques permit achieving 2,000 lines per mm. However, the material appears capable of achieving 4,000 lines per mm.

[1] A. Reich, G. H. Dorion, Optical & Electro-Optical Information Processing, Chap.31, p.567, MIT Press, Cambridge, Mass, (1965)

[2] Bell Laboratories Record <u>46</u>, 276 (1968)

A disadvantage of all the above materials is their relative insensitivity compared to silver halide emulsions.

Incident power density on the recording medium is relatively low in volume holography. With a helium-neon laser, exposure times for photographic films have been in the range of 10 to 15 minutes. The advent of the 1 watt argon gas laser has decreased this requirement by more than an order of magnitude to the 10 second range. Over the near term, this exposure time limits this technique chiefly to systems where rapid read-out is a requirement, but the data input can be relatively slow.

The design considerations for electro-optical and acousto-optical switched holographic optical memories has been examined.[1] Fundamental physical limits in basic electro-optical and acousto-optical processes limit the maximum value of the capacity-speed product. Speed is the rate at which the laser beam can be switched from one address to another randomly selected one, while capacity is the number of distinct beam positions the deflector device can produce.

$CSP = N_a^{1/2} \nu_a$

CSP = The capacity speed product

N_a = The total number of addresses in a memory

ν_a = The rate (addresses/sec) of random addressing

The highest capacity-speed product for electro-optical deflectors achievable with presently known materials is in the range of 10^9 sec.$^{-1}$. For current acousto-optical deflectors (400 MHz maximum available acoustic frequency), the highest capacity speed product is 10^8 sec.$^{-1}$. The maximum number of available addresses limited by practical deflector element size and optics is about 10^6 addresses.

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[1] F.M.Smits, L.E.Gallaher, Bell System Tech.J. 46, 1267-78, (1967)

If one seeks higher information density by storing bits in the form of a holographic arrays at each address, the sensitivity of the detectors employed and the light power reaching each bit become limiting factors. Using reliable lasers operating in the visible region with from 1 watt to 100 milliwatts output, one could expect to attain total memory capacities of 10^8 bits divided into address positions of 10^4 bits each with an address access time of less than 10μsec.

Holographic digital memory systems have a number of advantages:

(1) Reduced sensitivity to dust since the information about each bit is spread over the entire image area. The presence of dust will reduce image intensity, but not cause complete information loss.

(2) Uniformity of illumination is also not very critical.

(3) Exact positioning of the individual hologram is not very critical. Slight displacement of the beam with relation to the image will still permit reconstruction of the image.

(4) Complex arrays of focusing lenses are not required, eliminating optical losses.

On the other hand, reconstruction is very sensitive to the angular position at which the beam addresses the hologram.

Translational sensitivity is traded for angular sensitivity, since it is easier to design a mechanical system in which close angular tolerances are maintained in the presence of mechanical vibration and thermal changes than one in which absolute distances (spacings) must remain constant.

On the basis of calculations, the theoretical storage capacity of a 1 cm^3 alkali halide crystal has been determined to be 3×10^{11} bits[1]. Interestingly, if one were to sequentially record with a modulated 1 micron diameter laser beam laying down a two-dimensional array of bits in the same volume of medium (a series of 1 mil thick, 1 cm^2 slices) the theoretical maximum storage capacity is about 4×10^{10} bits. On this basis, depending on the ability to coat films of the medium less than a mil thick, the theoretical recording densities of the two techniques would converge in the limit. The relative simplicity, efficiency, access time, and economics of either direct writing or the holographic technique in approaching the theoretical information limit of a medium will be a decisive factor in practical system design.

A photo-image data storage unit has been reported which is capable of storing 100, 35mm holographic images on a one square inch potassium bromide crystal.[2] A helium-neon laser is used in the system. Work is under way to achieve a 1000 image storage capacity. The crystal element has a storage capability of 10^6 bits per cm^2.

Experiments have been reported in which 1000 holograms have been superimposed in the same area of a 9" square photographic plate.[3] Theoretical calculations indicated as many as 10^5 holograms could be obtained while retaining a practical signal to noise ratio (S/N) for read-out (10 db.) when an array of separated point sources (digital information) is the subject. The limitation appears to be not one of optical signal to noise ratio but one of available intensity and electrical S/N in the detector. Bell Laboratories has reported the ability to store temporarily up to 1000 holographic images on a crystalline cube

[1] P. J. Van Heerden, Appl. Optics, <u>2</u>, 764 (1963)

[2] Laser Focus, p. 12, March 14, 1966

[3] J. T. LaMacchia, D. L. White, Appl. Optics, <u>7</u>, p.91-4,(1968)

of lithium niobate.

Based on the dichromated gelatin holographic film reported above, L. K. Anderson[1] has described a holographic optical memory system for bulk data storage with a predicted capacity of 100 million bits of data with a random access time as short as one microsecond. For comparison, a typical twister memory using 16 permanent magnet twister memory modules has a capacity of 5.8 million bits and an average access time of about 4 to 5 microseconds. While this does not represent the largest possible twister memory - factors of large capacity, short access time, and cost warrant a searching exploration of other techniques. A 32 by 32 matrix of holograms with about 1.2 mm for each hologram (page) is employed as the storage plane. Electro-optic, X-Y deplection of the read-out beam projects reconstructed data on an 8 x 8 matrix of phototransistors. A hologram about 1 mm in diameter can readily store 10,000 bits of information. The current experimental system has a capacity of one thousand, 4,000 bit pages (4 million bits). The deflector used can address the 32 page by 32 page memory plane in 6 microseconds.

Recently, engineers from I.B.M.'s System Development Division reported on a laser memory system capable of retrieving blocks (arrays) of information from a 9" square holographic plate (photographic) in 10 microseconds.[2] This is a thousand times faster than current magnetic disc and drum storage units. The holographic display is read-out by an array of photodetectors. The system is reported to have a potential of storing a 100 million bits on the 9" square plate (2×10^6 bits/cm^2) which is a hundred times greater capacity than current magnetic devices.

[1] L.K. Anderson, Bell Laboratories Record, <u>46</u>, 318-25 (1968)

[2] N.E.R.E.M., Fall, 1968; Product. Engrg. <u>39</u>, 38 (Dec.,1968)

For comparison with the holographic approach to digital memory systems, consider two direct writing systems under development. Minneapolis Honeywell, I.B.M., and Precision Instrument Company are working with laser digital storage systems using thin film recording media in which the bits are put down sequentially by a modulated laser beam rather than as an array in a hologram, and read-out sequentially. In these systems, recording can be accomplished at very high rates.

Honeywell's system[1] employs an evaporated thin film of a compound of manganese and bismuth. The magnetic and optical properties of the compound polarize light passing through the film rotating it clockwise or counter-clockwise depending on the direction of thin film magnetization. Honeywell is reported to be using a 1W argon laser beam. Transmission of a low power laser beam does not disturb the magnetization pattern representing the stored digital information and rotation of the laser beam polarization plane can be readily detected. Data can be written or erased by pulsing the beam to high intensity and simultaneously applying a magnetic field. At 680 degrees Fahrenheit (produced by the high intensity, focused, laser beam), the managanese-bismuth compound loses its magnetization and as it cools will align itself with an applied magnetic field changing the magnetization pattern. The system has a capability of storing 10^6 bits/cm^2 with a read rate of 100 million bits per second. This is roughly 100 times faster than present magnetic devices.

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[1] D. Chen, J. R. Ready, R. L. Aagard, E. Bernol G., Laser Focus, p.18-22, (March 1968); Instrumentation Technology, 15, 14 (1968)

I.B.M.'s system[1] employs a europium oxide film at low temperature (20°K). The advantages of using a europium oxide memory material are large magneto-optic effects are produced permitting fast read-out rates, thermowriting at low temperatures requires much less energy, fast switching speeds can be used for the read-write lasers because of the low energy requirement, and small area magnetization reversals can be sustained. Using a 10 MW laser,bits less than 3μ in diameter were written in 10 nanoseconds. Experimental work indicated that operational temperatures as high as 77°K may be feasible in the future.

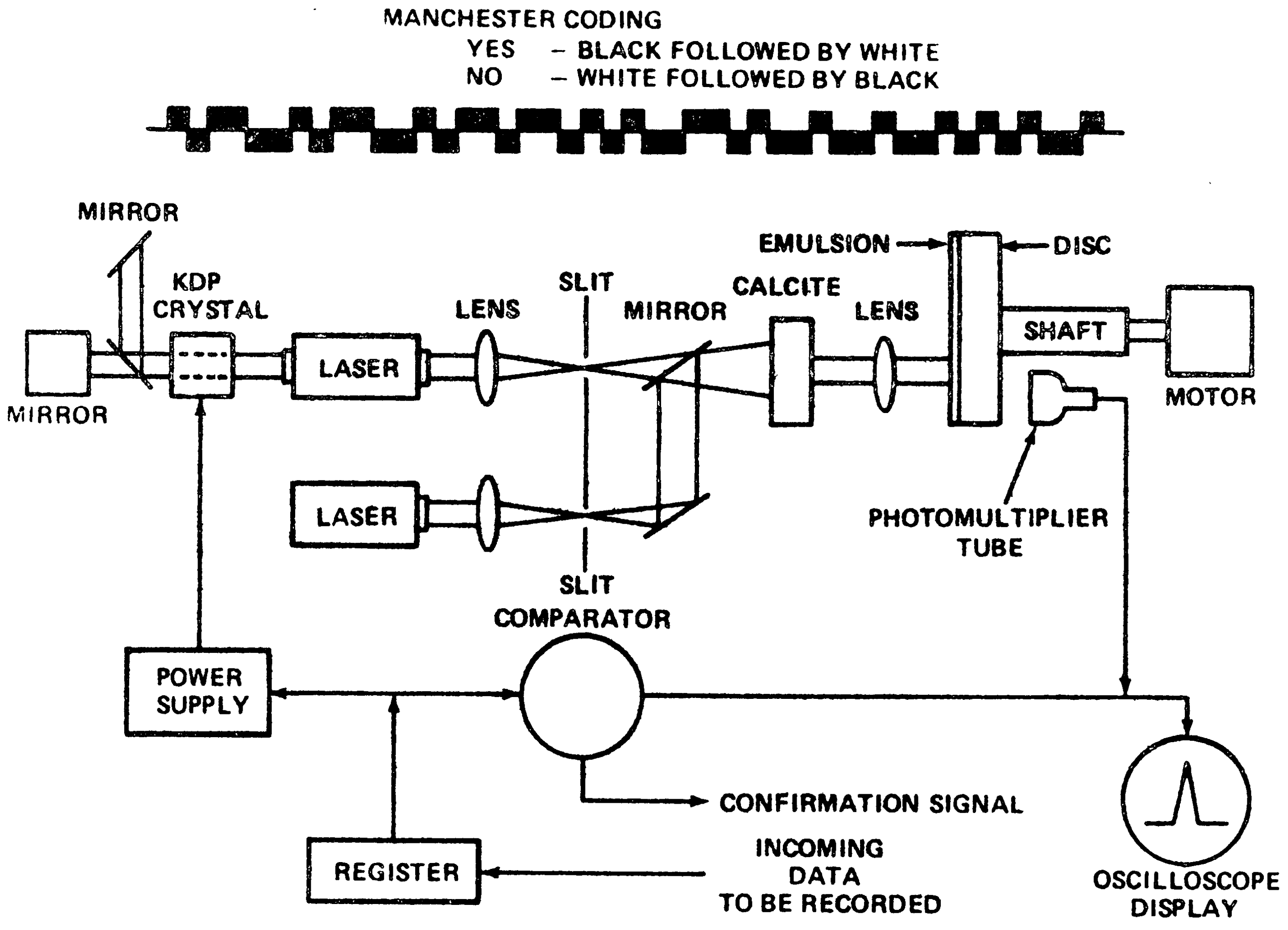
Work on a transparent ferrimagnetic garnet material suitable for magneto-optical memory has been reported by Bell Laboratories personnel.[2] A memory consisting of a close-packed mosaic of small thin Gd IG crystals operating at 14°K with a maximum density of 2.5×10^5 bits per square inch is proposed as practical.

Precision Instrument's system employs a one-watt argon laser beam which is frequency modulated by input recording signals to "burn" holes in a thin metallic film,[3] (metallic aluminum has been suggested) deposited on a polyester base. The beam is swept over the medium by a combination of tape movement and reflection from a rotating mirror (helical scan) or alternately by movement of the tape alone. 1.5μ "holes" are made on 10μ centers. A 1μ laser beam of lower intensity (3% of recording intensity) is used for read-out. The laser is kept in the same position and the film is driven at the same

[1] G. V. Fan, J. H. Greiner, J.Applied Physics, 39, 1216-18 (1968)

[2] J. T. Chang, J. F. Dillon, Jr., V. F. Gianola, J.Applied Physics, 36, 1110-11 (1965)

[3] Product Engineering, 39, 21-3 (May, 1968); Industrial Electronics 6, 153 (April, 1968)



''PHOTO STORE'' MEMORY SYSTEM

FIGURE 4

speed as during recording. A flying spot scanner guided along the track by remote controls directed by a galvanometer keeps the laser spot in the center of the track. A photodetector beneath the film serves as the read-out detector for the laser spot. The medium has a recording density of 2×10^6 bits/cm^2 and the system is capable of a read-out rate of 2×10^6 bits/sec. The manufacturer claims the recording tape has about 1000 times the capacity of present magnetic tapes. One limitation is that the recording process is not reversible. The record is permanent. In some applications, this could be an advantage. The degree of advantage could depend on relative cost per unit of storage among other factors.

Another direct writing, digital information storage system is Photostore, a data processor developed and used by the United States Air Force for automatic translation.[1] A laser beam focused by a lens is used to record photographically on a disc of film ten inches in diameter. Ten million bits of information are stored in one square inch (about 10^6 bits/cm^2). The recorded information comprises a very large dictionary and tables of grammar. Manchester coding is used, i.e. binary digits are recorded by two marks - a black followed by a white represents one binary digit, the reverse, a white followed by a black represents the other, Figure 4. The photosensitive film is attached to a metal disc mounted on a spindle with a large moment of inertia and is rotated at high speed, 1800 rpm, to give a million bit per second recording rate. The image being focused on the film is a rectangle which sweeps out a square recording. Simultaneously, a track border is recorded by using the same lens to form an image of a mask illuminated by an auxilliary source. Between the laser and the lens, nine crystals

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[1] G. W. King, Discovery, 27, 19-22 (1966)

of calcite shift the image over one mark width when the polarization of the beam is switched to that of the extraordinary ray by a KDP electro-optic crystal device. The unswitched polarization is that of the ordinary ray. The modulating voltage applied to the KDP crystal is gated electronically by the data to be recorded. Most high resolution materials are sufficiently transparent to transmit part of the beam to a photomultiplier tube. The current signal from the photomultiplier goes to a comparator to be matched with the original electrical signal which created the modulation. The comparator confirms the correct signal was sent and that an image was formed.

For a commercial system, recording rates of a million bits a second are desirable. To achieve sufficiently sharp images (minimum "smear"), the exposure time must be extremely short -- fractions of a microsecond. To ensure the marks have acceptably sharp edges, the modulation must be applied and become effective during a fraction of the exposure time -- about ten nanoseconds (10^{-8} sec.). During this period, ten thousand volts must be applied across the faces of the KDP modulating crystal. This is a severe problem and new materials having lower power requirements are becoming available and should permit practical applications operation.

DIRECT WRITING SYSTEMS

Currently, direct writing systems operate in essentially a facsimile mode. A modulated laser beam is scanned in sequential lines across the recording medium. The input signal to the modulator may be from an optical scanner of some type or from a specially formated, computer generated, magnetic tape.

Direct writing systems involve the following elements:

(1) A continuous wave laser source
(2) A modulator to impress information on the source beam
(3) A deflector to scan the modulated signal over the recording medium
(4) A recording medium in a transport device

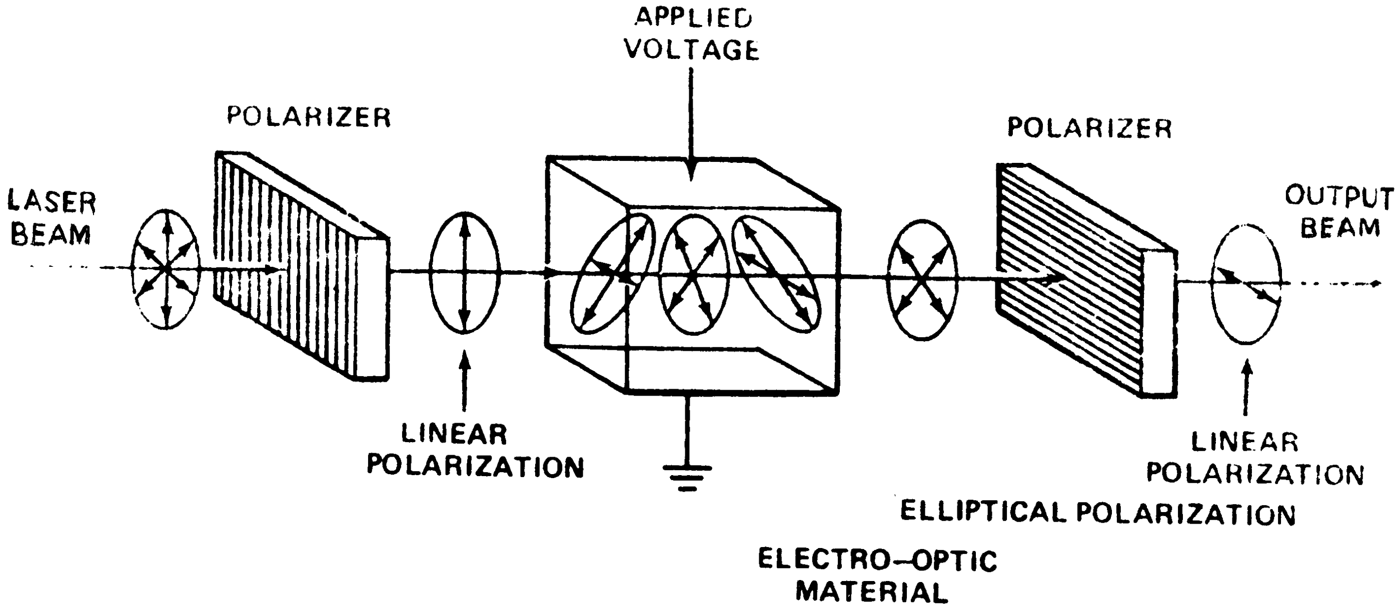
MODULATION

The basic means of modulating laser radiation is by exploiting the polarized nature of the beam.

When application of an electric field to an optical medium results in a perturbation of its refractive properties, the phenomenon is called the electro-optic effect. In some solids and in liquids, when the changes in refractive index are proportional to the square of the applied field, it is called the Kerr effect. In crystalline solids lacking a center of symmetry, changes in refractive index display a linear relationship to the applied voltage. This is called the Pockels effect. Rotation of the plane of polarization of a light wave as it travels through a substance in a direction parallel to an applied magnetic field is called the Faraday effect. A variety of gases, liquids, and solids show this effect.

Light polarized in a certain direction can have its plane of polarization rotated on emergence from devices employing these effects, Figure 5. By selection of proper cell thickness and applying sufficient voltage, the direction of polarization can be made to rotate 90°. A polarizer placed in the path of the emerging beam with its polarization axis oriented 90° with respect to

ELECTRO-OPTIC MODULATION



ELECTRO-OPTIC MODULATION – LINEARLY POLARIZED LIGHT ON PASSING THROUGH THE ELECTRO-OPTIC MATERIAL IS MADE MORE OR LESS ELLIPTICALLY POLARIZED DEPENDING ON THE MAGNITUDE OF THE APPLIED VOLTAGE THUS LIMITING THE EXTENT TO WHICH THE BEAM WILL PASS THROUGH THE SECOND POLARIZED ORIENTED AT 90° TO THE INITIAL POLARIZER.

FIGURE 5

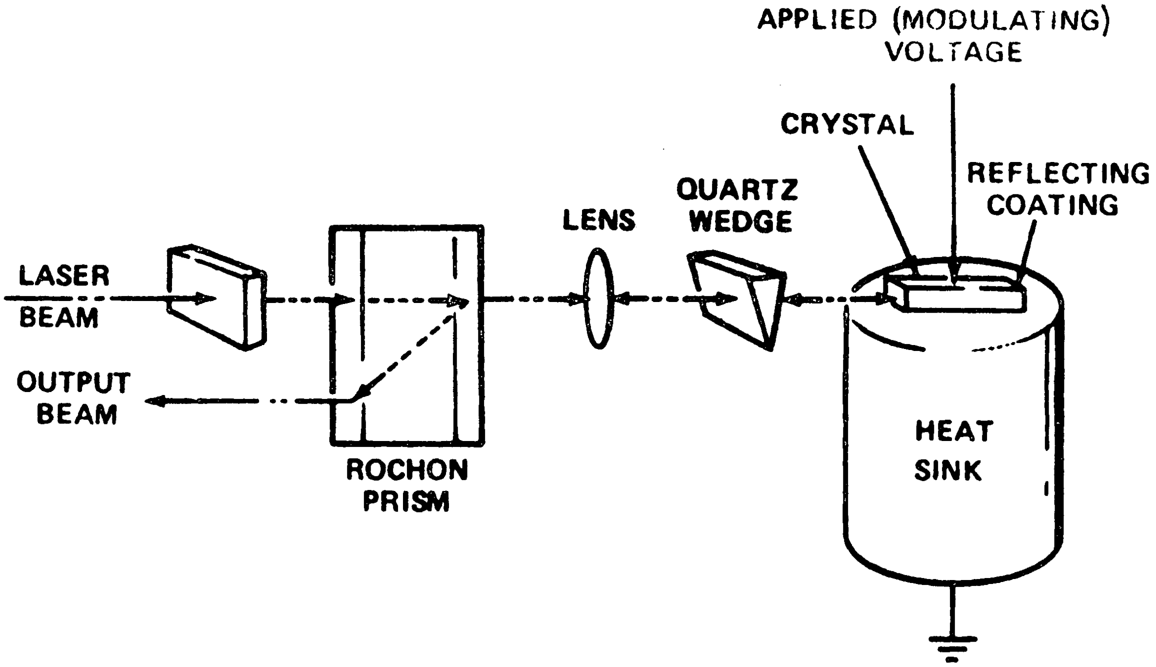
the plane of polarization of the light beam entering the electro-optic device will not pass light whose plane of polarization has not been rotated 90° by application of voltage to the device. By alternating the applied voltage one can "pulse code" modulate the light beam. A variety of crystals and liquids are used commercially in devices and others are being developed. Ammonium dihydrogen phosphate crystals and nitrobenzene (liquid) have been used commercially. A number of alkali tantalate niobate salts, i.e. potassium tantalate niobate (KTN), show promise of requiring lower power. Power requirements at high frequencies are a major problem in modulation using electro-optic devices.

Laser modulation has been achieved by placing an electro-optic crystal, i.e. lithium niobate inside a helium-neon laser cavity and deflecting the laser beam so as to miss the end mirror.[1] The usable modulation can be increased theoretically by as much as one hundred times provided no optical losses are introduced. Using an aperture in the above case to reduce the beam diameter resulted in a 6% loss but enabled an increase of about 50 times in diffracted power. In one set of experiments at 500 MHz, approximately one watt of RF power was needed to achieve a maximum.

A lithium tantalate modulator (Figure 6) has been reported to produce 80 percent modulation of the intensity of a red, helium-neon laser beam over a bandwidth of 200mc/sec. using only 200 milliwatts of power from a transistorized amplifier.[2]

[1] A. E. Siegman, C. F. Quate, J. Bjorkholm, G. Francois, Appl. Phys. Letters 5, 1 (1964)

[2] D. F. Nelson, Scientific American, 218, 17 (1968)
R. A. Laudise, Bell Laboratories Record 46, 3 (1968)



THE BEAM EMERGES FROM THE CRYSTAL ELLIPTICALLY POLARIZED AND THE COMPONENT OF POLARIZATION PERPENDICULAR TO THE INPUT COMPONENT IS DEFLECTED BY A ROCHON PRISM TO FORM THE OUTPUT BEAM.

LITHIUM TANTALATE CRYSTAL MODULATOR

FIGURE 6

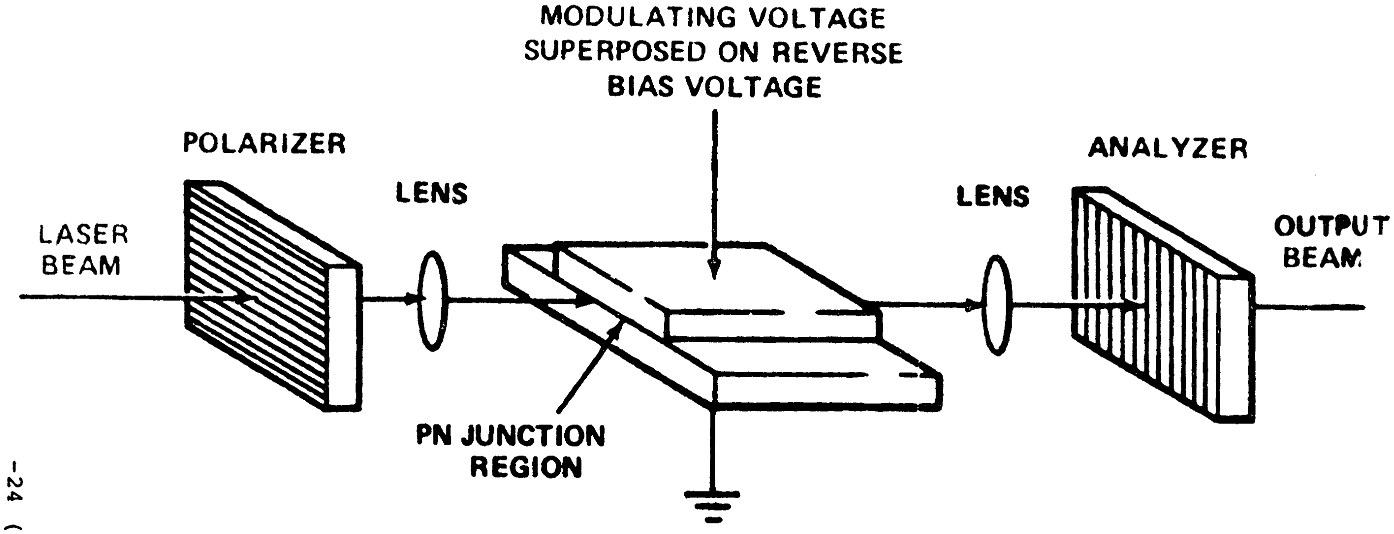
The p-n junction modulator makes use of an electro-optic effect in a semiconductor crystal, Figure 7. Because of the extreme narrowness of the p-n junction region, precise focusing of the beam is required. A constant reverse bias is used to augment the electric field across the junction while the modulating voltage is impressed on top of the constant field. Polarizers at 90 degress to each other are used at opposite ends of the device to achieve modulation. Power dissipation within the diode crystal is a major limiting factor. A 1.5mm long diode can modulate the intensity of a helium-neon laser beam by up to 80%.[1] About 150 milliwatts can be dissipated limiting the diode operation to about a 100 MHz per second bandwidth. Improvements in materials and development work on mounting and device design are needed. Mounting techniques to improve heat dissipation and design for multiple beam passes could extend the modulation range considerably.

An efficient magneto-optic modulator requires a material that gives the largest Faraday rotation per unit of optical loss from absorption, Figure 8. Crystalline chromium tribromide, the material frequently used, has to be cooled within a few degrees of absolute zero in order to achieve the desired magnetic properties. Recently, a region of very high transparency has been found in magnetic yttrium-iron-garnet (YIG) and it can be used at room temperature. A 40% amplitude modulation of a helium-neon laser beam has been achieved with a YIG-based device at a bandwidth of 200mc with a power expenditure of 0.1 watt.[2]

An alternate technique of intensity modulation involves use of an ultrasonic diffraction cell, Figure 9. The operation of this device is based on modification of the refractive index of

[1] D. F. Nelson, Scientific American <u>218</u>, 17 (1968)

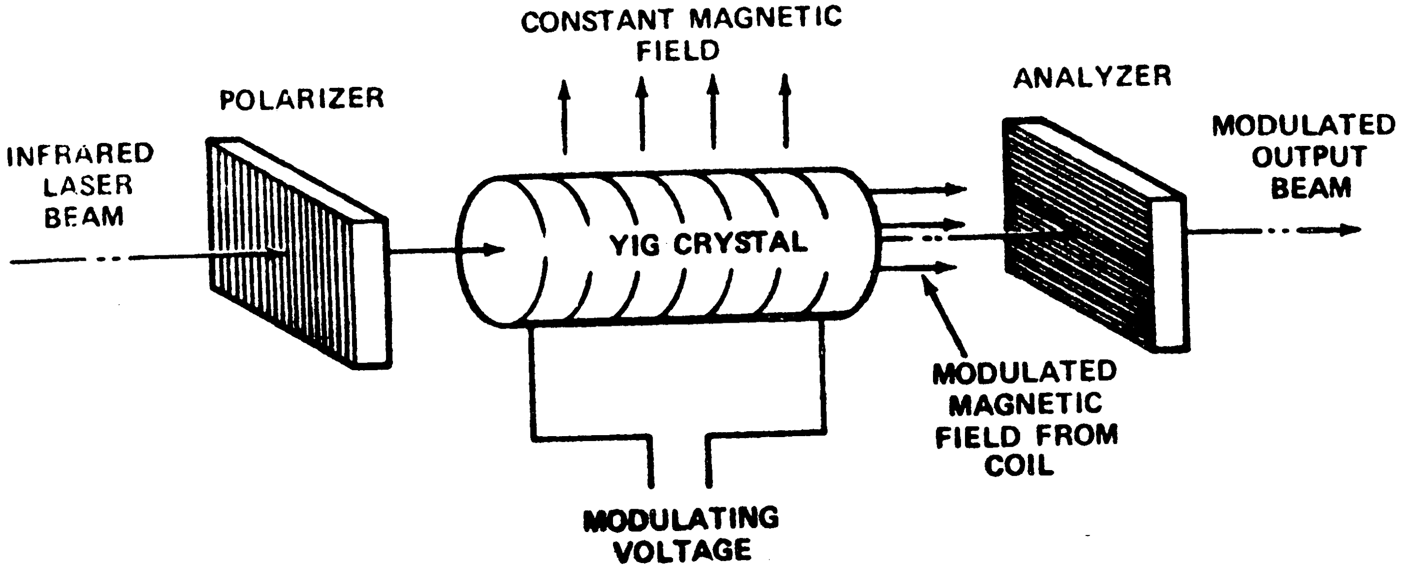
[2] Ibid



PN JUNCTION FUNCTIONS AS AN ELECTRO-OPTIC MATERIAL ELLIPTICALLY POLARIZING THE BEAM TO A DEGREE DEPENDENT ON THE MODULATING VOLTAGE.

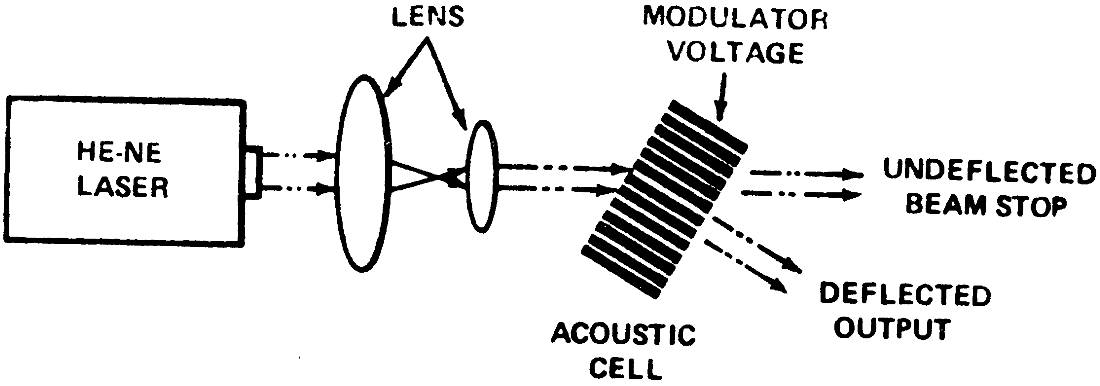
PN JUNCTION MODULATOR

FIGURE 7



MAGNETO-OPTIC (FARADAY EFFECT) MODULATOR

FIGURE 8



IN THE ACOUSTIC CELL THE PERIOD PATTERN OF LAYERS OF ALTERNATELY HIGHER AND LOWER REFRACTIVE INDEX IS CAPABLE OF ACTING LIKE A DIFFRACTION GRATING AND EFFICIENTLY DEFLECTING LIGHT THROUGH A SMALL ANGLE.

ULTRASONIC MODULATION

FIGURE 9

a transparent material, i.e. glass or water, by a stress wave. An ultrasonic stress wave traveling through a transparent material will deflect light in a manner comparable to a ruled diffraction grating. The angle of deflection will be directly proportional to the wavelength of light and the frequency of the ultrasonic stress wave. A control signal is used to modulate the stress wave. Use of a sufficiently small light beam coupled with a small or moderate carrier amplitude will result in diffracted light intensity variations corresponding to variations in the control signal. An optical stop is used to remove undefracted light. With a high index glass medium, operating frequencies in the 40MHz range have been achieved.[1] Bandwidth limitations and low contrast generally have been problems in this technique.

DEFLECTION

Basically, three types of devices have been employed to achieve deflection.

1. Mechanical Scanners involving use of electro-mechanical or mechanical driven mirrors.

2. Variable Diffraction Devices

    a. Electro-optic effects have been employed in a number of devices, i.e. a series of prisms, to achieve variable refraction at a dielectric interface or by an index gradient.[2]

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[1] R. Adler, I.E.E.E. Spectrum 4, 42-54 (1967)

[2] J. F. Lotspeich, I.E.E.E. Spectrum 5, 42-52 (1968)

b. Acoustic (ultrasonic) waves traveling through a transparent medium produce sinusoidal refractive index variations which can be used to deflect a laser beam.[1]

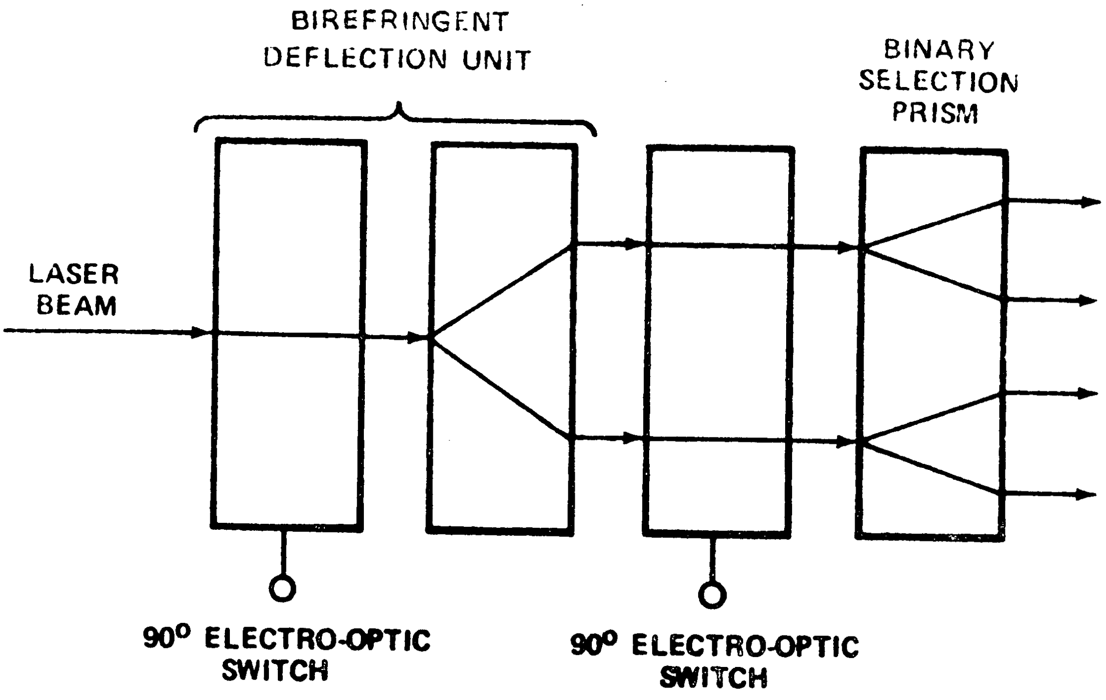
3. Birefringent Deflection Devices employing a combination of a polarization modulation element combined with a passive birefringent polarization discriminator (crystal). The polarization state of the incident laser beam is varied by the modulator and this variation is converted by the discriminator into a linear or an angular displacement to yield two distinct beams, Figure 10. A linear chain of these devices will produce a regular array of discrete beam positions.

Although an imposing array of deflection devices are available, system constraints for high speed, high information density recording rapidly converge one to limited approaches. The following requirements are minimal for microform recording:

(1) Resolution capability in excess of 100 lines/mm.
(2) Aperture size and focal length consistent with diffraction limitations.
(3) Dynamic optical surface uniformity during scanning.
(4) Ability of high speed scanning elements to sustain severe dynamic stress.

Phase front distortion must be reduced to negligible values for all components used in a high resolution deflection device. Theoretically, all the techniques can provide nearly diffraction

[1] R. Adler, I.E.E.E. Spectrum, 4, 42-54 (1967); A. Korpel, R. Adler, P. Desmeres, W. Watson, Proc. I.E.E.E. 54, 1429 (1966)



BIREFRINGENT DEFLECTION DEVICE

FIGURE 10

limited performance. Practically, optical distortion is presently a problem with electro-optic refractors using the new high sensitivity materials such as potassium tantalate (KTN), with variable refractors at high frequencies for which dielectric losses heat the medium non-uniformly, and for acoustic (ultrasonic) standing wave refractors.

Using cascaded binary birefringent deflection devices, resolutions (discrete spot positions) greater than 10^6 appear feasible with present technology.[1] Scanning rate is ultimately limited by power dissipation in the electro-optic crystals and is in the 10^6 deflections/second range for presently available materials. This type of device is best suited for random access deflection applications (digital recording).

For direct writing, computer output, and microrecording applications, scanning by electro-optic type deflectors is fundamentally resolution limited by diffraction effects and wave front distortion within the deflecting material. Temperature gradients play a role in the latter. Beiser[2] characterizes the maximum resolution of a linear gradient type deflector as follows:

$$R_{max} = \frac{1.46 \quad (W/\alpha\lambda)^{2/3}}{\eta^{1/3}}$$

where R_{max} = maximum number of spots per scan width W

W = scan width in same units as λ

λ = wavelength of light beam

α = aperture and flux shape factor ($1<\alpha<1.5$)

η = index of refraction of the material

For $W=16$mm, $\alpha=1$, $\lambda=6328$Å and $\eta=1.5$, the equation yields R_{max} = 1100 spots per scan or 34 line pairs per mm. Using practical ranges of values, it is apparent that the gradient type of scanning device will be limited in attainable resolution for high reduction (small W) applications.

[1] R. K. Lee, Jr., F. Moskowitz, Appl. Opt. 3, 1305 (1964)

[2] L. Beiser, J. Optical Soc. Am. 57, 923-31 (1967)

For comparison, Beiser[1] gives the following relation for maximum resolution of a rotating mechanical type deflection device, Figure 11.

$$R_{max} = \frac{2.4 \quad B}{N \; S \; W} \times 10^6$$

where B = signal bandwidth in MHz
N = number of scanning elements per rotation
S = rpm
W = width of scan line in inches
R = resolution in line pairs/mm

For W = 16mm, S=30,000, N=4 and B=20, the equation yields 626 lines/mm

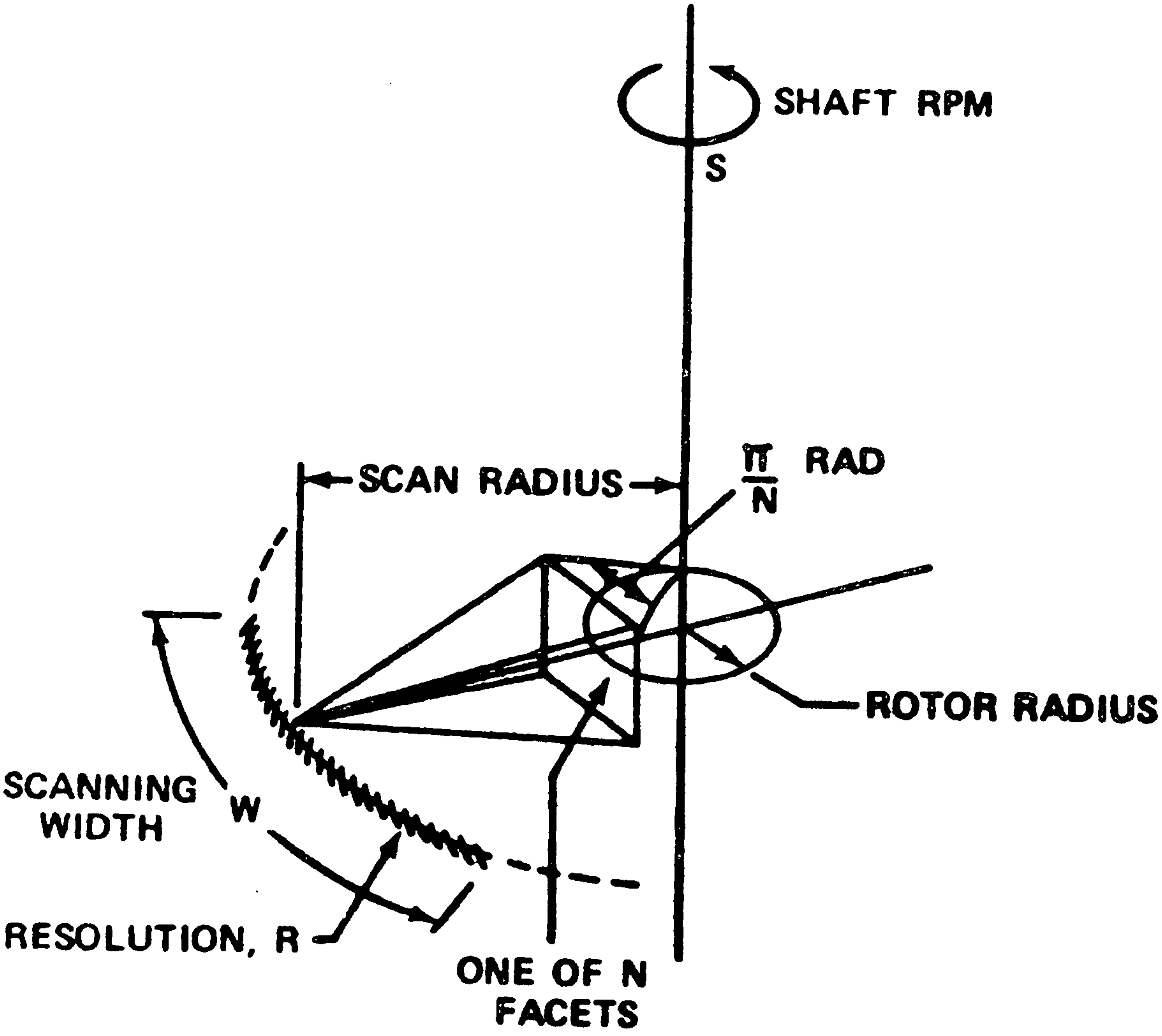
The diffraction constraint requires relatively large source dimensions. If the source is a mirror, the high velocities required precludes vibrational systems. Mechanical oscillation devices of a few millimeters radial dimensions are constrained to operation in the 5 - 20 KHz range.

Rotational systems may be designed to operate with stability for source dimensions in the centimeter range at shaft speeds in the hundreds of thousands of revolutions per minute. With such a device, one revolution will convey N linear scans at extremely high velocity. Depending on modulator bandwidth limits, microform recording is achievable with this deflection technique.

MECHANICAL SCANNER RECORDING SYSTEMS

The recording systems demonstrated to date with computer output capability have used helium-neon or argon ion lasers, electro-optic modulators, and moving mirror scanners.

[1] L. Beiser, J. Optical Soc. Am., 57, 923-31 (1967)



$$R = \frac{2.4\ B}{NSW} \times 10^6$$

B = MH^2
W = INCHES
S = RPM
N = NO. FACETS
S = RPM

SCAN PARAMETERS FOR A POLYGON SCANNER

FIGURE 11

Advanced multifaceted, rotating mirror technology developed for ultra high speed framing and streak camera photography has been applied in laser recording systems to achieve deflection.[1] These devices should be considered as single frequency devices governable over a large range. Frequency cannot be changed rapidly. The unidirectional rotation of the mirror unit leads to a sawtooth-like scanning action -- one scan line per mirror face. Maximum scan rates are limited by the peripheral velocity tolerance of the mirror. Material bursting speed and surface distortion due to the large centrifugal acceleration are the major limitations. Mirrors of beryllium are commonly used because of its material strength. Beryllium mirrors can be taken up to a velocity of 500 meters per second. At these speeds, the mirror surface takes on a cylindrical distortion which must be corrected by the optics. At 500 meters per second, a hexagonal rotating mirror could resolve 5000 spots at about 31,000 sawtooth scans per second allowing 10 per cent of the scanning time for retrace. In a typical scanning device, a collimated input beam is brought in through a vacuum-tight window and deflected by a beryllium mirror driven by a gas turbine. The deflected beam passes through the aperture of a spot forming lens. The focused spot moves sequentially along a straight line across the recording medium. High stability of the rotating mirror ensures sequential line scans are precisely superposed. The vacuum system reduces aberrations due to gas turbulence. The deflector is ball-bearing suspended to give long life under suitable environmental conditions. This device yields diffraction limited resolution at very high speeds of operation. Synchronized film motion provides an x-y or two-dimensional recording. Figure 12 shows schematics for typical rotating scanner recording systems.

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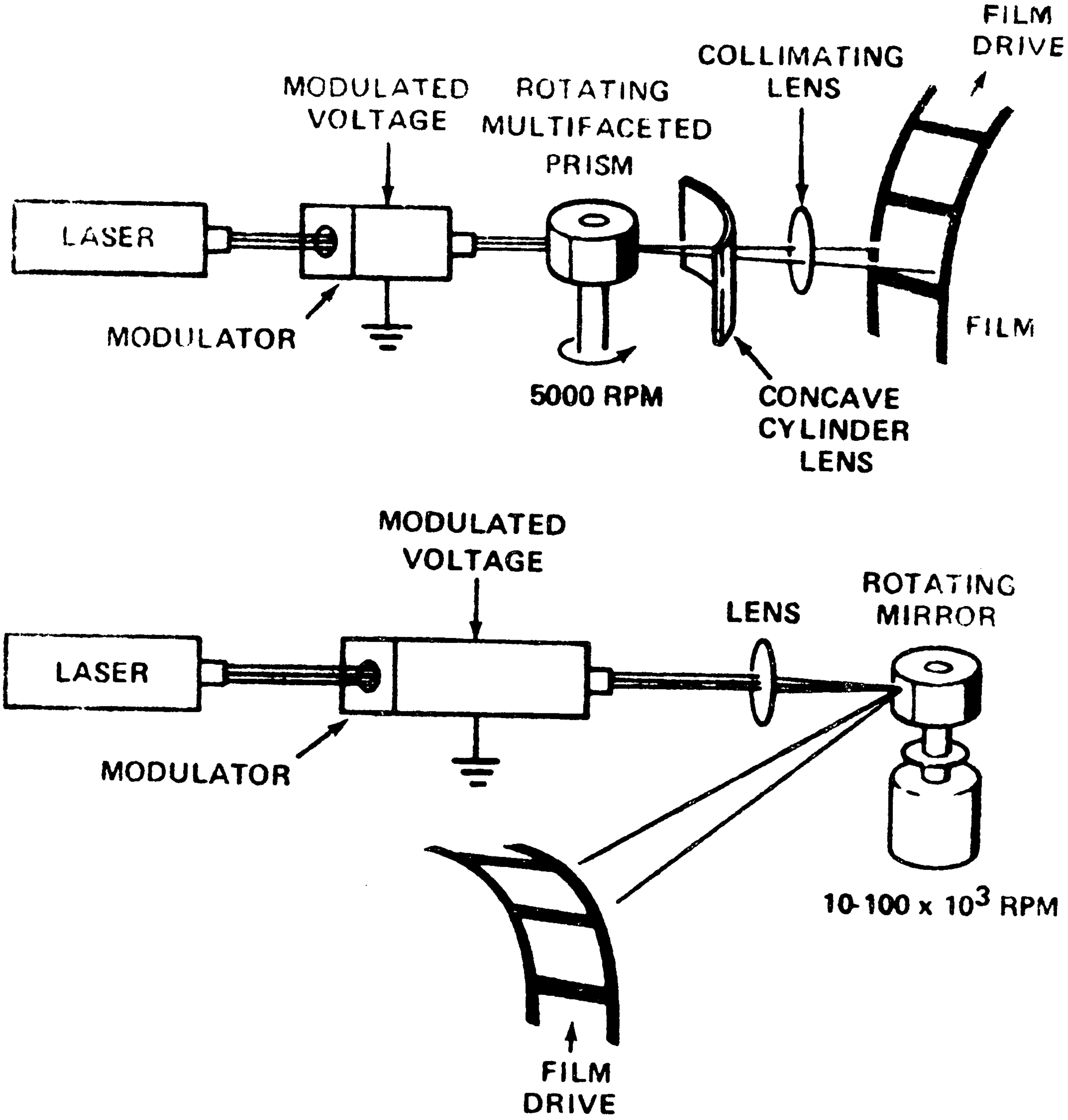
[1] B. J. Thompson, Applications of Lasers to Photography and Information Handling, Chap. 3, p., 51-69, SPSE (1968)



SCHEMATIC DIAGRAMS OF
MECHANICAL SCANNING RECORDERS

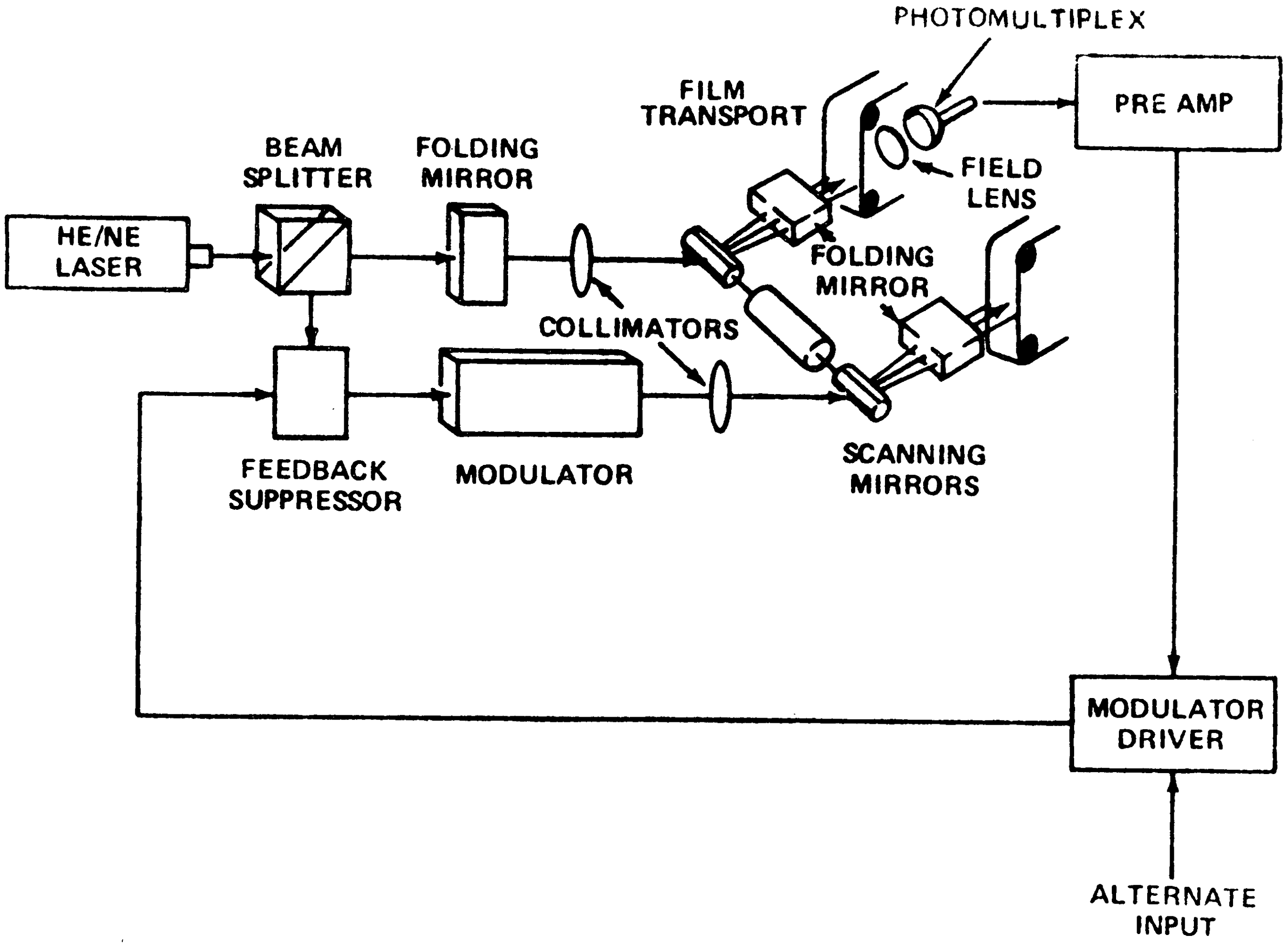
FIGURE 12

A laser scanning device for readout and recording of information from photographic film using rotating mirrors has been built for the Avionics Laboratory at Wright Patterson Air Force Base.[1] The system capability was demonstrated by scanning a photographic transparency and reproducing it via laser on a strip of recording film, Figure 13. A helium-neon laser beam is split into two parallel beams which undergo essentially identical optical processing. The read-out beam is focused to a 0.01 mm spot and passed through a transparency to strike a photomultiplier tube with an intensity depending on the image density in the emulsion. The photomultiplier output boosted by a preamplifier controls a modulator device interposed in the path of the recording beam. The modulator brightens or dims the recording beam before it strikes the recording film depending on the density of the corresponding scanned spot in the transparency. For synchronized scanning, a film transport motor advances the transparency and recording film strip. Simultaneously, a scanner motor acts on mirrors to deflect readout and recording beams synchronously. The modulator was operated at 5MHz. The superimposed film transport motions and mirror tilt yield continuous line scanning of the transparency and the recording film analogous to the scanning patterns of a video tube. To achieve high packing density would require more complex optics and synchronous drive systems. This would require considerable modification of the system.

Dresser Systems has built a computer controlled printer based on a laser line scanner recorder.[1] A computer output modulated, helium-neon gas laser beam is scanned across a 40-inch film. A four-sided mirror rotating at 12,000 rpm is used to lay down 8,000 spots per line. The system has a capability of recording 16 grey scale levels and operates at a one megacycle rate.

[1] B. J. Thompson, Applications of Lasers to Photography and Information Handling, Chap. 3, p. 64 SPSE, (1968)

[2] R. F. Stengel, Design News, <u>21</u>, 142-3 (1966)



SCHEMATIC OF MECHANICAL SCANNER FOR READ OUT AND RECORDING

FIGURE 1

R. C. A. has reported a Laser Beam Image Reproducer.[1] The input signal used to drive the laser beam modulator is the video signal from a Vidicon Tube. A 12 micron laser spot is scanned across the concave surface of the film plane to produce 6,000 spots per scan line. A four-sided pyrimidal mirror rotating at 24,000 rpm is used to produce the line scan. The film plane motion results in a final picture with 5,000 lines. The system is presently a 5 megacycle system but is capable of being upgraded.

Mechanical scanners using a double scanning arrangement have been reported also. In these systems an x-y or raster scan is achieved while holding the film fixed. This requires both a line scan and a frame scan. The speed ratio and the number of faces of the scanners are adjusted to produce the required relationship.

None of the systems described using mechanical deflection are outputting high information density (microform) film. The scan line widths would have to be decreased and the bandwidth would have to be increased or the rate of rotation decreased to achieve density. The latter would result in a slower recording rate. With the former, the power required and the rate at which the applied field can be turned on and off in the modulator device are limiting factors. Attainment of a 16mm scan line width with a 1-5μ spot size would be required for microfilm output with the R. C. A. system, for example.

Carlson, et al of the National Cash Register Company[2] have reported recording microimages on metallic and organic thin film layers using a helium-neon laser. Effective recording rates of

[1] A. S. Milinowski,J. Opt. Soc. Am., <u>54</u>, 1406A (1964)

[2] C. O. Carlson, E. Stone, H. L. Bernstein, W. K. Tomita, W. C. Myers, Science, Vol.<u>154</u>, #3745, p.1550-1 (1966)

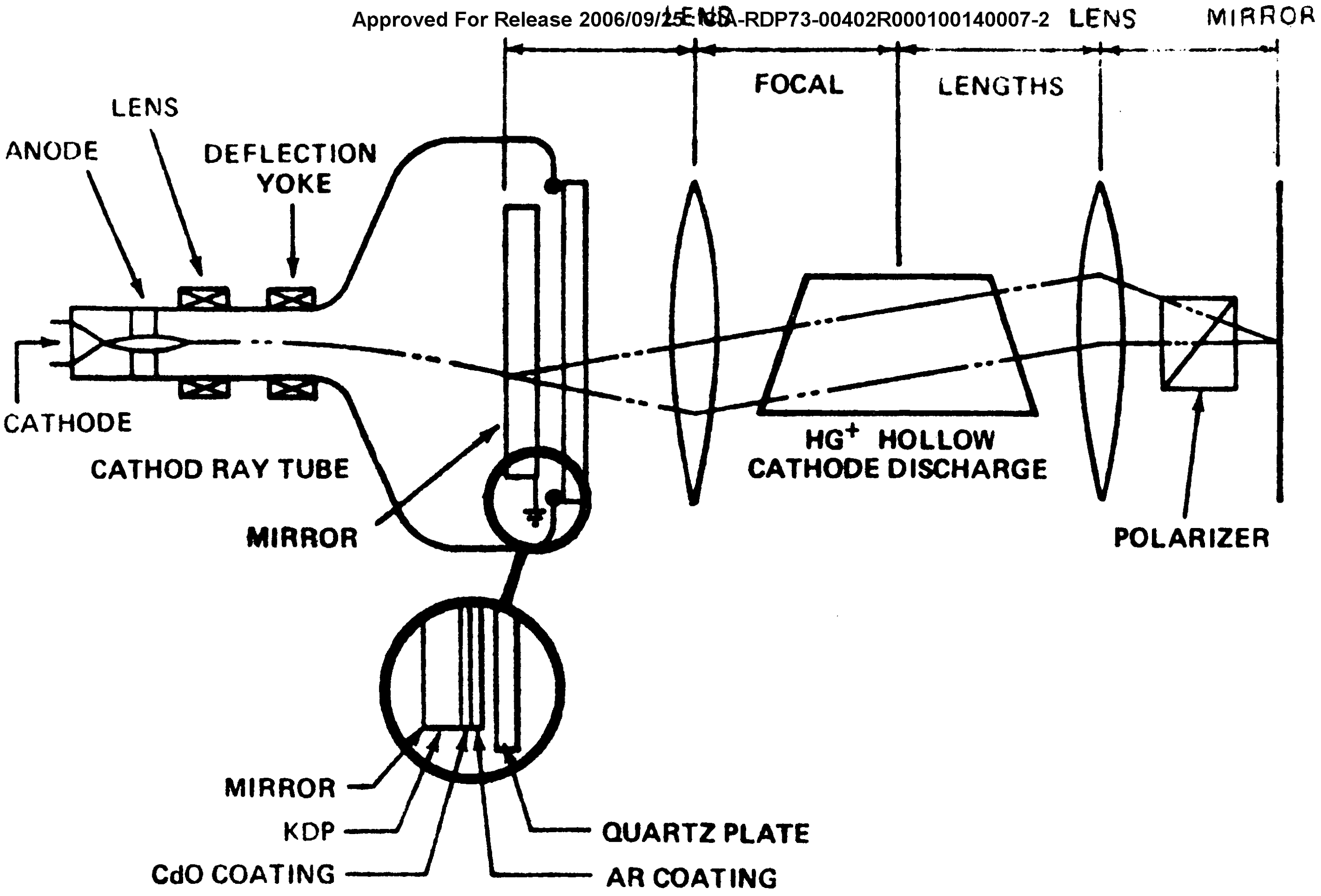
10^5 - 10^6 spots per second were attained laying down line scan widths in the 2.0 micron range. Attainable resolution can be estimated to be about 250 line pairs per mm. They reported recording a page of the bible by direct document input via a facsimile-type optical scanner. An ultrasonic diffraction grating type modulator was used in the laser recorder. The recording objective had a numerical aperture of 0.2 with a useful flat field diameter of 3mm. The 3mm contained 1600 scan lines. 1200 scan lines were used in recording the document page. The authors observed that the resolution of the recording was limited by the optical resolution of the document scanner.

Development of a computer output, microfilm recorder system featuring stroke writing or randomly scanned outputs is highly desirable. To achieve this, development of an inertia-less laser scanner is mandatory.

Two recent developments involving the use of an electron beam in conjunction with a laser cavity show promise for achieving inertia-less scanning in the future. In both cases, deflection of the imaging electron beam produces deflection of the laser output.

(1) Electron Beam Scan Laser

In this device, an electron beam induces localized birefringence in an electro-optic crystal by depositing a charge on its surface, setting up a field (applied voltage). A degenerate, flatfield, conjugate laser resonator is formed by two mirrors and two lenses spaced such that one of the mirrors is imaged onto the other, Figure 14. One mirror consists of a sandwich of electro-optical and birefringent materials which reflects and changes the state of polarization of an incident light beam. The change of state of polarization prevents laser



ELECTRON BEAM SCAN LASER

FIGURE 14

action from occurring. Laser action can be induced by directing the electron beam to a particular point on the sandwich. Laser beam action will take place only at this point with an intensity and direction directly controlled by the electron beam. The electron beam is controlled and deflected by conventional electron optical techniques. The device operates like a cathode ray tube (CRT) whose faceplate has been replaced by an energy amplifier.

Such a device has been operated in a scanning mode over a field 22mm in diameter with a spot size of about 0.45mm using a Westinghouse 10SP electron gun at 10KV accelerating voltage.[1] A single line could be swept in 7ms. With a beam current of 0.007μA., the optical power was 100μW; about three orders of magnitude greater than for a similar spot on a conventional phosphor CRT.

(2) Electron Beam Pumped Lasers

In the early 1960's, consideration was given to use of energy from an electron beam to pump a semiconductor laser. Basov[2] et al reported achievement of stimulated emission in cadmium sulfide in 1964. Successful achievement of laser action in indium antimonide and indium arsenide bombarded by a 20KEV beam (spot diameter about 0.2mm) at a current of about 2ma was reported by Benoit a'la Guillaume and Debever.[3] The semiconductor samples used featured polished surfaces and were 100μ thick. Using a gallium arsenide sample with parallel polished surfaces, about 200μ apart, soldered to a copper heat sink at the bottom of a liquid helium dewar, Hurwitz and Keyes[4] achieved laser action using a 50KEV electron

[1] R. V. Pole, R. A. Myers, NEREM Rec. 7, 244-5 (1965); ibid I.E.E.E. J. Quantum Electronics QE-2, 182-4 (1966)

[2] N. G. Basov, O. V. Bogdankovich, A. G. Devyatkov, Symposium on Radiation Recombination in Semiconductors, Paris, France, (7-28-64)

[3] C. Benoit a'la Guillaume, T. M. Debever, Symposium on Radiation Recombination on Semiconductors, Paris, France (7-28-64)

[4] C. E. Hurwitz, R. J. Keyes, Appl. Phys. Letters 5, 135 (1964)

beam (0.5mm spot) and 0.2μ sec. pulses (1,000/sec.). Beam currents of 1-2 a/cm^2 were required to reach the threshold. Above the threshold at about 3 a/cm^2, a number of modes were excited. All of these experiments involved radiation emitted from a crystal at right angles from the direction of the beam.

A number of authors[1] have reported electron beam excitation of laser action in specially grown semiconductor crystals and in semiconductor junctions. Laser action at 4900Å with a peak power output of 350W at 100°K has been reported using electron beam pumped cadmium sulfide crystals grown in an atmosphere of excess cadmium. An accelerating voltage of 60KV and a 22ma beam were required to achieve the peak power output for a 0.5μ sec. pulse with a repetition rate of 3KHz. Laser action was observed at considerably lower power output levels at temperatures up to 250°K. The potential for electron beam pumping of materials such as cadmium sulfide, cadmium selenide, zinc sulfide, zinc telluride and other high band gap materials opens the possibility of producing semiconductor lasers in the visible and even in the ultraviolet regions.

An approach for a scanning beam laser proposed by Lax[2] involves construction of a thin slab of semiconductor of the order of 100 to 200μ thick with polished, parallel, plane surfaces, Figure 15. The slab may be in one piece several centi-

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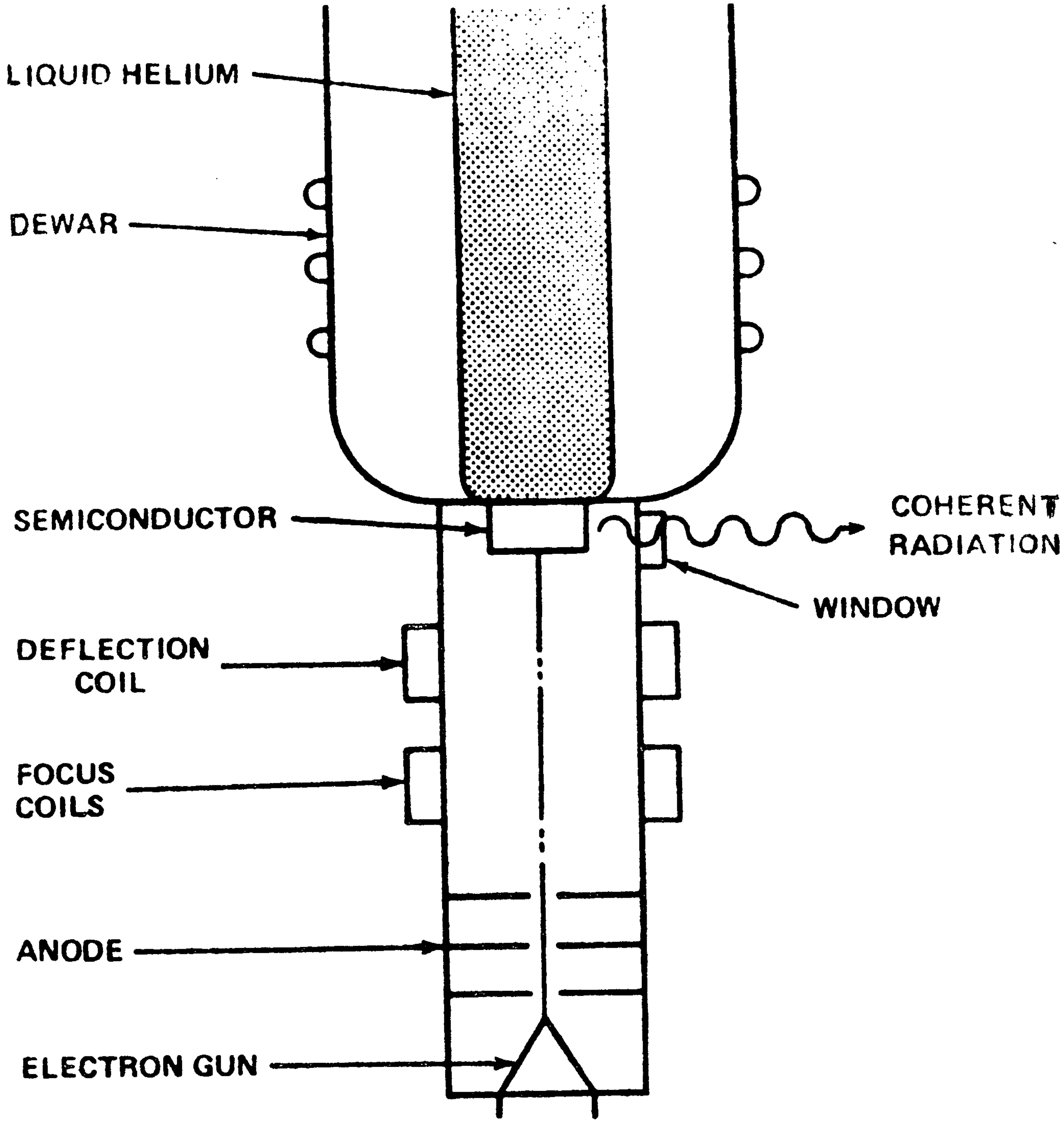
[1] C. E. Hurwitz, Appl. Phys. Letters 8, 121 (1966); C. E. Hurwitz I.E.E.E., J. Quantum Electronics QE-2,27-28, (1966); G. E. Fenner, J. Appl. Phys. 37,4991 (1966); C. Benoit a'la Guillaume, J. Debever, Compt. Rend. 261, 5428 (1965); ibid, I.E.E.E., J. Quantum Electronics, Q.E.-2, LXV (1966)

[2] B. Lax, Solid State Design 6, 19-23 (1965)



ELECTRON BEAM-SEMICONDUCTOR LASER

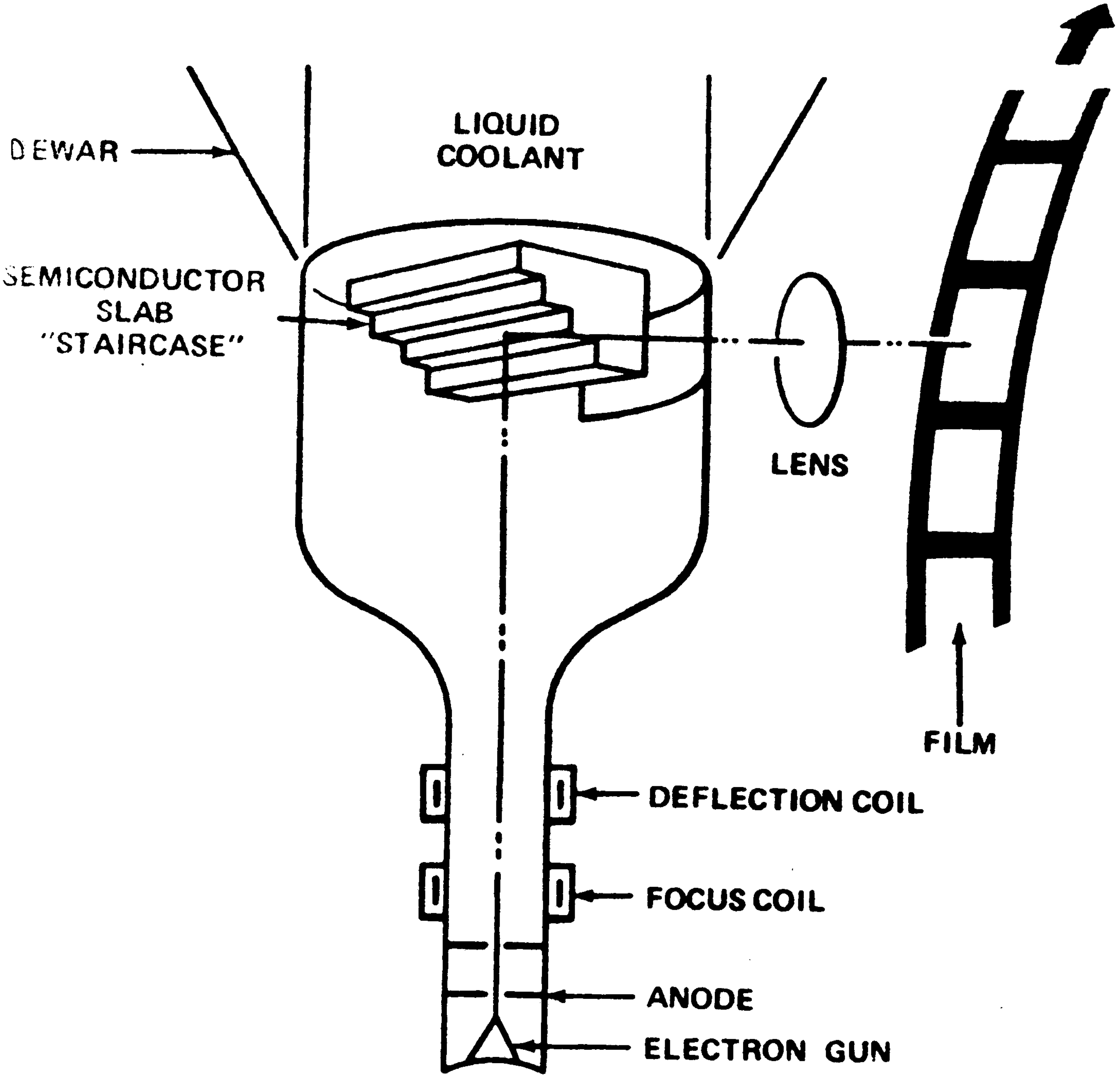
FIGURE 15

meters long or a mosaic of several pieces in juxtaposition to one another of equivalent total length. The slab is mounted in an evacuated tube on a copper sink at the bottom of a liquid nitrogen or helium dewar. The evacuated tube also contains an electron gun, intensity focusing, and accelerating grids to yield 20-100 KEV energies. The tube is equipped with deflection coils or plates for sweeping and positioning the beam along two horizontal dimensions. The beam may be swept across the semiconductor controlled by the deflection unit. When the current reaches a threshold value, coherent emission will emerge at right angles to the polished side and exit through a window in the tube. Power must be kept below an average of about 1-10 watts per centimeter of length depending on the cooling capacity.

Lax also proposed achieving a capability of a frame or raster output by constructing a "staircase" (multiple array) arrangement of slabs combined with a lens - the "Scanatron". The electron beam would be alternately swept and indexed across a series of laser slabs on the "staircase", Figure 16. In this arrangement, the beam would be in contact with a different portion of the semiconductor at each increment of time. The increased mass and greater volume of material in contact with a heat sink should enable continuous laser emission with much greater power output. Deflection of the electron beam to a stop or turning the beam on and off synchronously with the input signal could provide modulation.

Another geometry is also possible involving stimulated emission from one of the crystal faces excited by the electron beam. Basov, et al[1] proposed and reported stimulated emission from gallium arsenide in which the light beam emerged from the

[1] N. G. Basov, O. V. Bogdankovich, V. A. Goncharov, B. M. Lavrushin, V. Yu Sudzelovskii, Soviet Phys. Doklady 11, 522-4 (1966)



ELECTRON BEAM SCAN LASER FOR "FRAME" RECORDING

FIGURE 16

bombarded face. Tait, et al[1] reported stimulated emission from cadmium sulfide selenide from the face opposite the bombarded face.

Implementation of scanning laser beam - electron beam pumped devices might become feasible with advances in the state of the art. There are design and engineering problems involved in the combination of vacuum tube, low temperature, and semiconductor technology. Attainment of appropriate laser beam spot size and power density at high recording rates are problems in achieving microfilm output. The combination of these technologies offers many desirable features. Achieving a synergistic combination over the near term presents a major challenge to systems engineers and materials scientists.

RECORDING MEDIA

Use of photochromic, alkali halide, and metalized polymer films as recording media has been discussed earlier in systems applications. There are three other types of imaging materials which are being employed for laser recording applications:

(1) Silver halide emulsions
(2) Dry Silver films
(3) Thermoplastic Xerography (Frost Imaging)

(1) Silver Halide Films

In silver halide films the resolution is limited by photon scattering and film granularity. Generally, a 25μ spot on a 7.5μ center to center spacing appears practical. Two Eastman Kodak films have been used. Eastman Kodak SO-243 has a resolution of 500 lines/mm and is sensitive at 6328Å. Eastman Kodak Type 6496H is sensitive to the green region while Type 649F is a red

[1] W. C. Tait, J. R. Packard, G. H. Dierssen and D. A. Campbell, J. Appl. Phy. 38, 3035 (1967)

Spectral Sensitivity - 3M 'and Dry-Silver Films

Comparison of Experimental Type 784 and Red Sensitive Dry-Silver Film

Energy Required for Net Density of 1.0

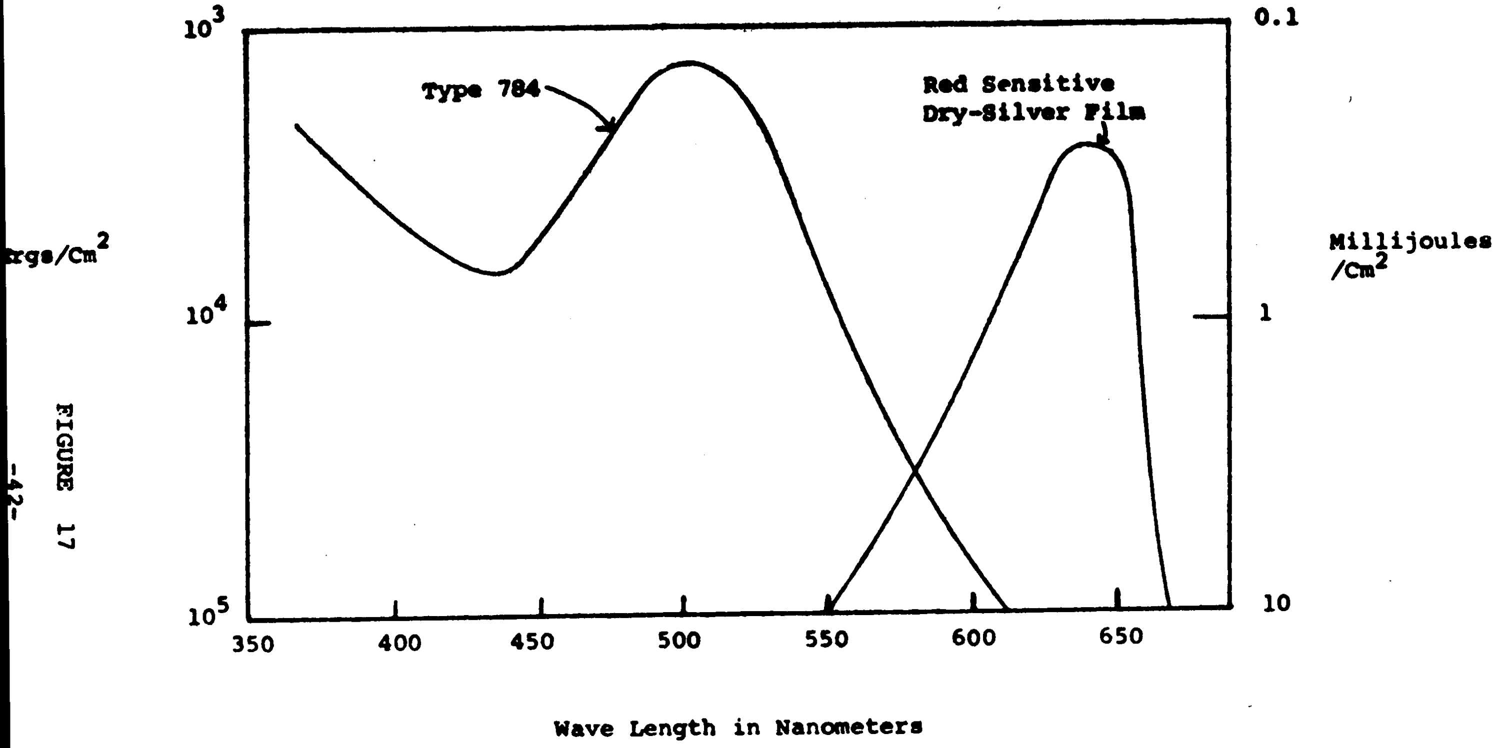


FIGURE 17

sensitive material. These films have a resolution of 2500 lines/mm.[1] Type 649 has an ASA of about 0.003 while SO-243 is 200-300 times more sensitive at 6928Å.

Agfa-Gavaert Type 10E70 Holographic film has been used with a helium neon laser[2]. The emulsion has a thickness of 5μ, a peak spectral sensitivity between 600-650mμ, and a resolving power of about 2800 lines per mm. The film appears to have excellent properties for both holographic and optical data recording.

(2) Dry Silver Films

Type 784 red sensitive Dry Silver film (λmax=6400Å) can be recorded on with a 2.5μ spot helium-neon laser beam. Resolution is limited by photon scattering and film granularity. Dry Silver films can be thermally processed on line with the recording process. Figure 17 shows the sensitivity for a given spectral range for two types of Dry Silver films, "green sensitive" Type 784 and an experimental Type 784 "red sensitive" film.

(3) Thermoplastic Xerography - "Frost Imaging"

Urbach and Meier[3] have reported the making of phase holograms by thermoplastic Xerography. A phase hologram alters the phase rather than the amplitude of the reconstruction wavefront. The recording medium consists of an organic photo conductor film

[1] M. Lehman, Photography for Optical Measurements, Stanford U. Electronics Lab, Stanford, Cal.; Kodak Materials for Pictorial Holograms (Aug. 1965), Eastman Kodak Co., Rochester, N.Y.14650.

[2] S. A. Frecska, Applied Optics 7, 2312-14 (1968)

[3] J. C. Urbach, R. W. Meier, Appl. Optics 5, 666-667, (1966)

overcoated with a thin insulating thermoplastic film. The films, coated on a conductively coated, glass substrate, are corona charged, exposed, recharged and then developed by a stream of hot air. As a result of the hydrodynamic behavior of thin, charged, fluid layers, the deformation proceeds most rapidly in a particular spatial frequency range determined chiefly by thickness and to a lesser extent by the applied voltage. A complete cycle of operation from initial charge to final image can be made in a matter of seconds. Automation of the process is feasible leading to fractions of a second processing times. Optimum choice of process parameters can lead to an essentially grainless recording free from scattered light. Thus, the unwanted background of light scattered from grains, i.e. silver halide emulsions, is avoided. In thermoplastic xerography, the basic carrier of information is the deformation pattern which follows the holographic carrier and is inherently smooth and noise (scattering) free. Laser light (6328Å) from a helium neon laser with an output power of 0.8MW was used. The photographic speed attainable with this medium was estimated to range from 0.1 to 0.03 ASA. This material offers advantages of direct on-line processing and low grain.

SUMMARY

Considerable progress has been made toward implementing high information density, digital memory systems based on laser sources. High information density, direct writing (scanner) systems based on laser sources are feasible via rotating mechanical scanning devices. Seeking out specific combinations of laser source, modulator, deflection device and recording media to meet performance requirements for specific systems applications

economically is the challenge to systems designers and engineers. High information density, direct writing systems with stroke or character writing capability are still in research stages and will require scientific and engineering advances over the next 3-5 years to bring this capability to the systems application stage.