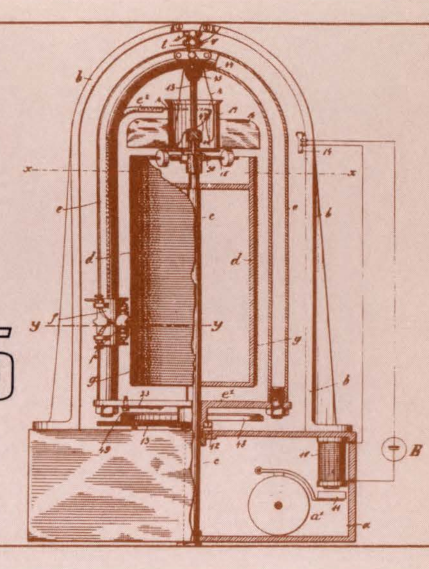
INSTRUMENTATION TECHNICAL INFORMATION NUMBER 5



DATA RECORDING WITH THE LASER

by Samuel Bousky

INTRODUCTION

Present day technology is forcing an increasing need for data storage at greater bandwidth and for data retrieval in shorter access time. The answer to both appears to be a requirement to reduce the spatial storage area per bit on the recording medium; or in other words, to increase the data packing density in terms of bits per square inch. A typical high quality magnetic data recorder capable of 6 megahertz (MHz) bandwidth and better than 40-dB signal-to-noise ratio (SNR) utilizes an 0.0100-inch track width, 0.0025-inch space between tracks (guard band), and an 0.00016-inch (4-micron) bit length. Such a system is capable of spatially storing about 0.5 megabits/inch^2 of tape surface. New equipment of about the same bandwidth and SNR, now being readied for product status, has increased the packing density to 1.3 megabits/inch^2.

Recent work at Ampex in electron beam recording on high resolution photographic film has shown that SNR of 40 dB can be attained with round spots of about .0002-inch (5-micron) diameter. Allowing a guard band width equal to a spot diameter, the spatial packing density would then be 12.5 megabits per inch^2 or about an order of magnitude greater than attainable in magnetic recording.

Data recording with light on photographic film is almost as old as photography itself. The ability to record at large bandwidth with small spots has been limited by available light sources and source brightness. The advent of the CW laser suddenly changed this situation and made available not only sources of significant brightness but also output light beams of good monochromicity and collimation. Laser sources permit the attainment of optical systems operating at the diffraction limit. Thus very small spots of light of the extremely high brightness necessary for large bandwidth and high packing density, are now attainable.

While the laser has opened new vistas in data recording it has brought with it problems of its own. The technical areas require careful evaluation before such instrumentation can enter into reliable product status. The more important problem areas include: spot formation, scanning, modulation, recording, and readout.

THE RECORDING SPOT

The theoretical basis for the formation of diffraction limited spots was worked out about 100 years ago. The impetus for this analysis was provided by the problems in astronomy wherein collimated light (starlight) of uniform intensity distribution filled a finite aperture to form a spot (star image). Such a spot is an "Airy disc," that is, a bright central maximum surrounded by a series of diminishing concentric rings as shown in Figure 1. The x and y coordinates are spatial, the z coordinate is light intensity. The size of the spot is determined by the f number of the optical system, that is, focal length divided by aperture. The size is defined as the diameter of the first dark ring.

The light from a laser source does not have uniform intensity distribution across the beam but is ideally gaussian. The spot which is formed also has gaussian distribution and therefore has no dark rings for specifying spot limits. A more practical definition in laser work is to define the spot size at the points where the intensity falls to 10% of maximum. Thus even though the distribution is not of ideal gaussian shape, the size definition is practical.

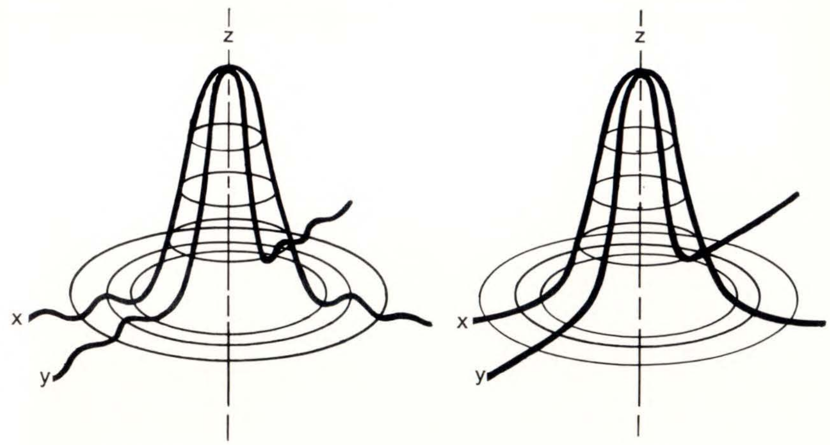
The envelope of the ray bundle forming a diffraction limited spot may be represented by a hyperbola of revolution as shown in Figure 2. The effective spot diameter d_e (at the waist) is given by:

$$d_e = k \lambda f = \frac{k \lambda F}{A}$$

where f is the working f number at the lens (or focal length, F, divided by beam aperture, A), λ is the wavelength of light, and k is a constant depending on intensity distribution and method of defining spot size. If size is specified at the 10% points, then k = 1.33 for an Airy disc and 1.27 for a gaussian input beam the size of which in turn is specified at the e^{-2} points.

In a scanning system, however, the spot is in motion. The recording medium observes an integrated effect of spot distribution in the direction of scan. The cumulated exposure in the center increases thus *reducing* the effective spot size (i.e., the 10% points shifted closer together). On the other hand, the spot size may be *increased* if the lens aperture is not sufficiently larger than the input beam size to avoid excessive cutting of the distribution skirts. Consideration must also be given to depth of focus when working with small spots. The focal depth is proportional to the square of the spot size. A spot as small as 40 μinches may increase by about 10% in a distance of 20 μinches whereas a spot of 200 μinches has a focal depth of 5000 μinches for a comparable change.

The light power in the spot required to effect a recording exposure depends upon spot size, recording bandwidth, and sensitivity of the



AIRY DISC DISTRIBUTION GAUSSIAN DISTRIBUTION

FIGURE 1

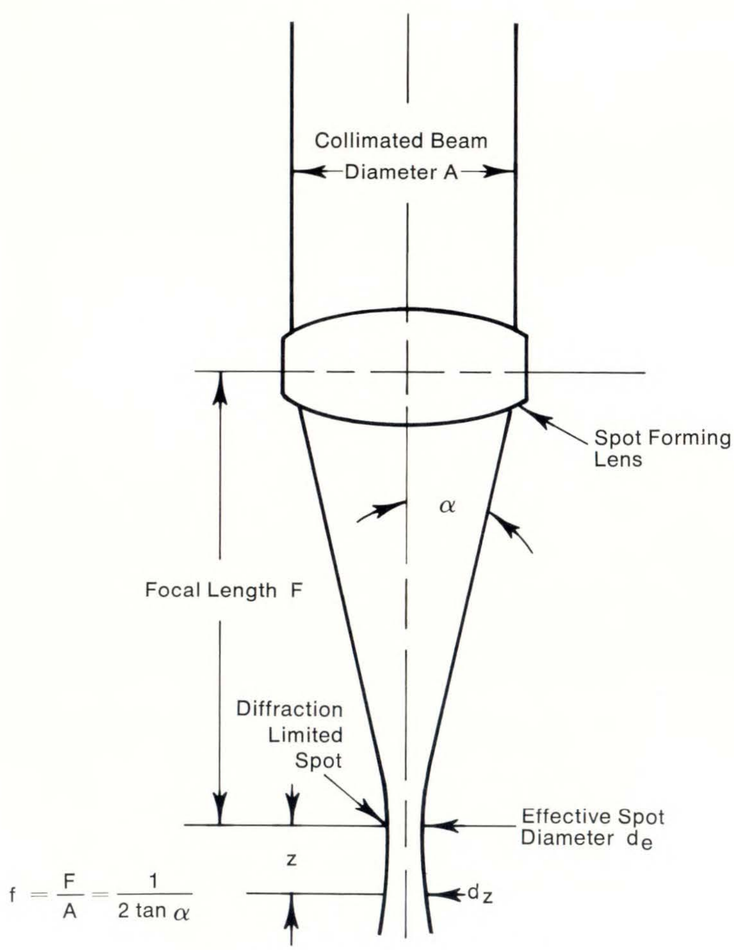


FIGURE 2. Spot Forming Schematic

medium. Spectrographic type films at 50 megahertz bandwidth require about 0.1 to 2 milliwatts in a 200 μinch (5-micron) spot to develop a density of 1.0. Present direct print-out photochromic materials on the same basis would require 2 to 5 watts of light power.

SCANNING

The most effective present method for wide-band recording is that of successive scans across the width of the recording film while it moves lengthwise. Each scan line may include several thousand spots or bits; a 5-micron (200 μinch) spot would produce over 10,000 spots per scan line on 70-mm film, and over 22,000 on 5-inch film.

Several electrical methods for producing scan line deflections of light beams have recently been demonstrated on a laboratory basis. These include electro-optical methods employing changes of refractive index or birefringent switching, acoustic interaction with light, and interferrometric techniques. All such methods are presently limited to a few hundred spot diameters deflection; none seems yet feasible for thousands of spot deflections.

Mechanical scanning methods presently show the greatest promise. Such scanning is effected by mechanical rotation and may be classified into three fundamental categories based upon the location within the spot forming ray bundle that scanning deflection is introduced. The method found to be the most capable of long scan lines at large bandwidth with the least optical and mechanical scan line distortion is entrant scanning, in which the ray bundle enters a fixed lens in such a way that the bundle always passes through the lens pupil while the entrant bundle scans through an arc. A typical system capable of 50-MHz bandwidth on 70-mm film may employ an octagonal mirror rotating at 67,000 rpm and supported on air lubricated bearings to insure positional accuracy.

MODULATION

A successful method of modulating laser beams utilizes the linear electro-optical effect of suitable crystalline materials. Suitable configurations of such crystals will produce a rotation of light polarization with applied voltage as a beam traverses the crystal. The polarization rotation may be made linearly proportional to applied voltage. To convert to an intensity change requires passage of the output beam through a polarizer. This latter conversion, however, is not linear but follows a sine-squared function. By biasing the modulator crystals at the midpoint of the sine-squared curve, a region of adequate linearity for data recording may be obtained. Figure 3 shows the harmonic distortion introduced by the modulator as a function of peak signal amplitude normalized to the half-wave voltage. Modulation of 60%, which corresponds to a factor of four from minimum to maximum light, introduces 4% distortion.

In a Lithium Niobate modulator developed by Ampex, correction circuits in the driving amplifier maintain total harmonic distortion to within 1½% for the 4:1 intensity range. This modulator takes 130 volts to cover the 4:1 range, is flat within ±1/2 dB from dc to 6 MHz, and requires driving power of 0.4 watts per megahertz of bandwidth. The modulator has been driven at bandwidths of over 100 MHz. The state of the art of electro-optic modulators is such that they are no longer a limitation in recorder design.

RECORDING

In the data recording process we consider the storage of electrical signal information for later retrieval and linear conversion to substantially identical electrical signal information. The recording medium (photographic film) is, however, not linear. A typical transfer characteristic for photographic film is the D — Log E curve (i.e., density, versus log exposure) as shown in Figure 4. The straight line portion of this curve may be represented by:

$$D = \gamma \log E$$

where γ is the slope of the straight line portion. Now if we consider the exposure E to be proportional to the input signal e_i, and the transmittance T of the recording to be proportional to the readout signal e_o and since:

$$D = \log \frac{1}{T}$$

then:

$$\frac{1}{T} = E^{\gamma}$$

and we may write:

$$\frac{e_i}{e_o} = k\frac{E}{T} = k\,E \cdot E^{\gamma} = k\,E^{\gamma+1}$$

From which it is apparent that to make e_o linearly related to E_i, γ must be −1. The negative value of γ dictates that the recording be a positive rather than a negative process. The curve of Figure 4 represents a negative process which would require making a print to attain a positive. The record/readout process has higher quality if the recording is made on a direct positive film.

The size of the spot limits the spatial bandwidth of the recording medium. The spatial bandwidth is measured in line pairs per millimeter (or cycles/mm). Figure 5 shows the modulation transfer factor for square wave response of the product of spatial frequency and spot size. Thus at a modulation transfer of 70% (3-dB attenuation) the $d_e f_s$ product is 470. This shows that a 10-micron spot would be down 3 dB at a spatial frequency of 47 line pairs/mm. The reciprocal of the $d_e f_s$ product (times 1000) gives the number of spot diameters per cycle for a given attenuation. Thus at 3-dB attenuation there are 2.1 (i.e., 1000/470) spots per cycle. These basic relationships are important in recording system design.

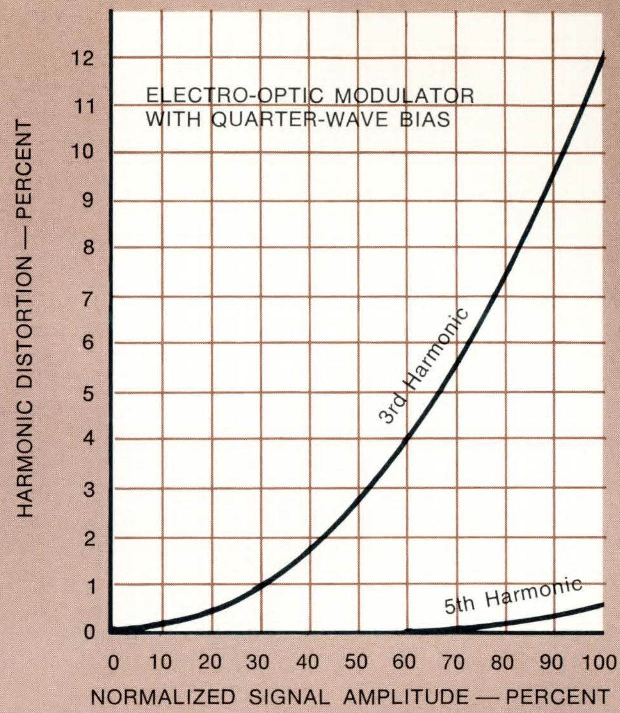


FIGURE 3. Distortion for Biased Electro-optical Modulation

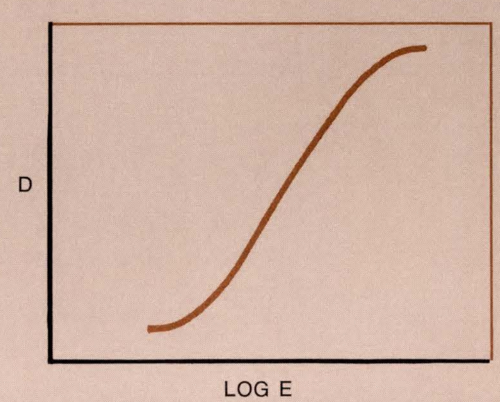


FIGURE 4. Film Transfer Characteristic D-Log E Curve

It is also important that a high degree of uniformity in spot size, shape, and intensity be maintained during recording. These factors are affected by variations in the amount of light reflected during the scan, by variations in the angle at which the spot arrives at the film, by the thickness of the emulsion layer, and by the precision of film positioning at the focal surface.

READOUT

Recorded data, to be of value, must be capable of retrieval. Considerable work on data readout by line tracking has been done by electron beam and many of the techniques developed are applicable to laser beam readout. Besides the ability to lock-on and track the recorded line during readout, errors caused by changes in the film due to processing, errors caused by variations in film transport, and errors caused by optical inaccuracies must be handled by the line tracking system. This requires means for small rapid spot deflections both in the longitudinal and transverse directions.

Certain electro-optical materials such as Lithium Niobate, Barium Sodium Niobate, etc.

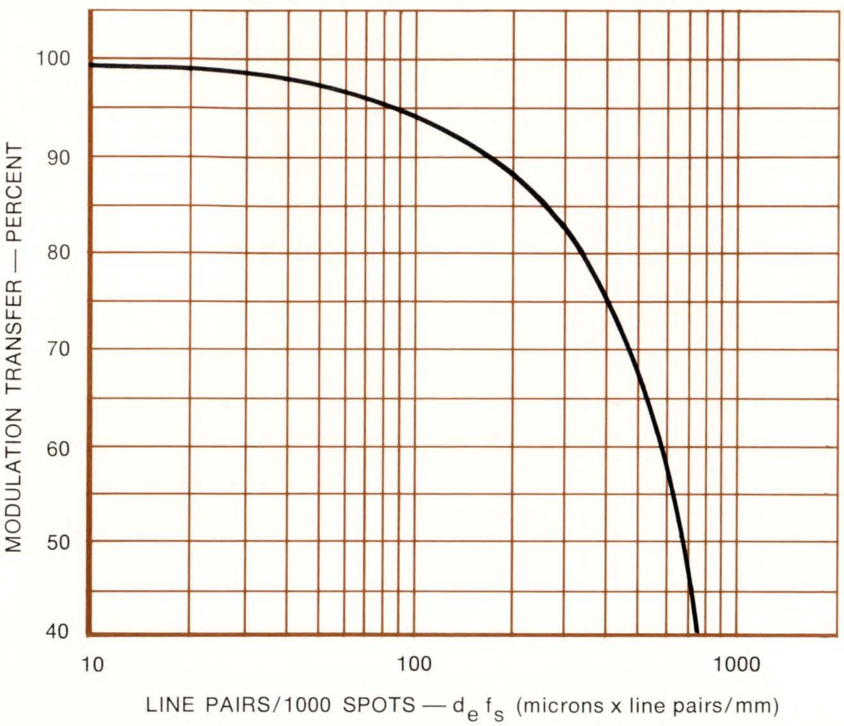


FIGURE 5. Square Wave Aperture Response

enable beam deflections through 3 to 5 spot diameters to be made at megahertz rates. In the film travel direction, however, deflections of perhaps 30 to 50 spot diameters at much lower bandwidth are required to maintain synchronization between the transport servo and scan line position. This can be obtained by electro-mechanical means. A combination of the two is indicated.

In order to maintain data continuity during readout, a small amount of data overlap can be provided at the line start and end, but then a switching function is required similar to that employed in magnetic recording. In laser readout however, two switching operations per line are required. One photodetector observes the start and a little more than the first half of each line, while another observes a little more than the remaining half and the end of the line. Switching between them then takes place in one direction at the line center and the other direction at the line end. Techniques for time base correction through the use of pilots and delay lines can be employed which are similar to those used in magnetic recording.

CONCLUSION

The added availability of light coherency from a laser permits the use of a new dimension in laser readout. Special techniques of data recording and readout utilizing the interference of light similar to that employed in holography is already showing great promise in faster data access, data analysis, and data processing. Instrumentation for data storage, retrieval, and analysis by laser beam is still in its infancy but it appears destined to occupy a significant position in future systems.

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