Optical Head Design for 1TB Optical Tape drive

Mahdad Manavi
Aaron Wegner, Qi-Ze Shu, Yeou-Yen Cheng
LOTS Technology, Inc.
1274 Geneva Drive
Sunnyvale CA 94089
manavim@msn.com
tel +1-408-747-1111
fax+1-408-747-1687

Abstract

A multi-channel Optical Head has been developed to be incorporated with an Optical Tape Drive that enables greater than 1TB capacity and greater than 25 MB/s data transfer rate on a 0.5 mil thick, 0.5 inch wide optical tape that fits in a 3480 style cartridge. The optical design has been optimized to perform at 532 nm with maximum through put in the write path. With use of a 0.6 NA objective lens, sub-micron size marks can be written on a WORM type phase change medium. A single laser, a hologram, and a multi-channel modulator increase reliability and manufacturability of this design.

Introduction

The need for a high capacity and a fast data transfer rate tertiary storage device is continually increasing. With the abundance of inexpensive high capacity magnetic disk drives, the explosive growth of information content on the Internet, and the need to save and keep data electronically for a long period of time, an increasing demand is continuously generated for high capacity tertiary data storage devices. We are developing a high performance Optical Tape Drive at LOTS Technology as a solution to this huge data storage problem. This Optical Tape Drive provides a nominal 25 MB/s data transfer rate and a nominal 1TB capacity in a 3480 style cartridge form factor.

Some of the advantages of optical tape drive are as follows. Optical tape provides much higher capacity per removable media unit than any storage device in the market. Very high data transfer rate is readily available for a given tape speed with increasing number of laser beams acting as parallel channels. Media is archival with greater than 30 years life span. The optical tape drive offers non-contact recording and read-back which result in zero head and tape wear. The tape transport mechanics have minimal physical contact with the tape further enhancing tape operational lifetime by reducing tape wear. Last but not the least, the high tape capacity results into fewer media mounts; thus causing less wear in robotics and cartridge.

The Optical Tape Drive consists of an optical head, a tape transport, and electronics. A multi-channel Optical Head has been developed to be incorporated with the Optical Tape Drive that supports the underlying required system specifications. I will discuss the intricate system design tradeoffs as they relate to the Optical Head design.

Design approach

In optical data storage, minimum mark spacing is one of the factors that determine the smallest signal amplitude available to the read channel. In a conventional peak detection method, the convolution of the read beam with written marks determines the data signal amplitude. Once minimum mark spacing and track spacing are established, the capacity is determined less the overhead. Obviously encoding efficiency is also a contributor to the bit density calculation.

To set a data transfer rate, two degrees of freedom are available. Once is the tape speed and the other is number of channels. At high tape speeds, the tape control becomes difficult and optical tracking servo bandwidth may become unreasonable. For a large number of channels, a flat field objective lens becomes necessary to focus the beam array to the flat tape surface. However, to achieve a high capacity, it is desirable to use a high numerical aperture (NA) objective lens to allow recording of sub-micron size marks. Unfortunately, increasing the numerical aperture of the objective lens and increasing the field flatness go against each other. In other words, the design task becomes extremely difficult to fulfill both criteria of high NA and field flatness. Therefore, the final design becomes a compromise among the tape behavior, optical tracking bandwidth, and the objective lens design.

Table 1 shows some options in changing the minimum mark spacing and track spacing to achieve the required capacity. For a 1 TB (Terra Byte) user capacity and 35% overhead, the raw capacity must be 1.35 TB. This is equivalent of 10.8 Tbits. For 450 m of tape, the areal density becomes 1.44 Gbits/in^2. Keeping this number constant, one can calculate various mark spacing and track spacing that result in 1 TB user capacity. Figure 1 shows various combinations of number of channels and tape speed for a given minimum mark spacing to achieve desired user data transfer rates. PPM (2,7) channel and 35% overhead were assumed for this calculation.

minimum mark spacing (um)	TPI	track spcing (um)
0.8	30236	0.84
0.85	32126	0.79
0.9	34016	0.75
0.95	35906	0.71
1	37795	0.67

Table 1 –Mark spacing & track spacing that result in 1 TB capacity

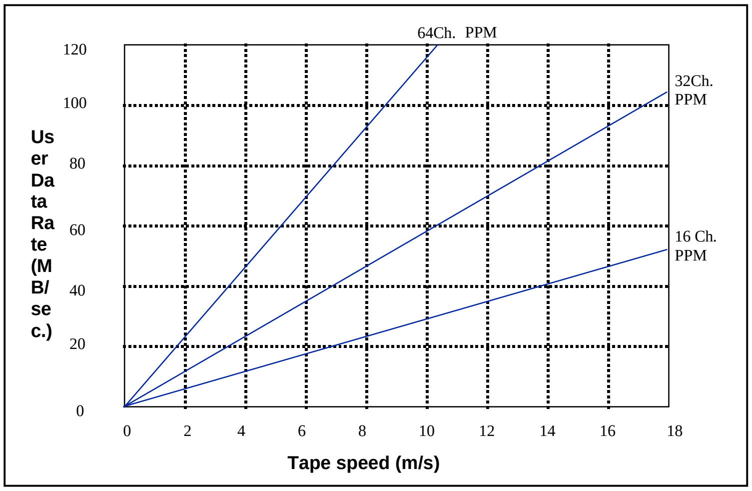


Figure 1 –Number of Channels and Tape Speed Versus Data Transfer Rate

Determining factors on choice of minimum mark spacing and track spacing are data optical resolution and track to track data crosstalk.

Drive structure

Drive layout is shown in Figure 2. It consists of an optical head, a tape transport, and supporting electronics

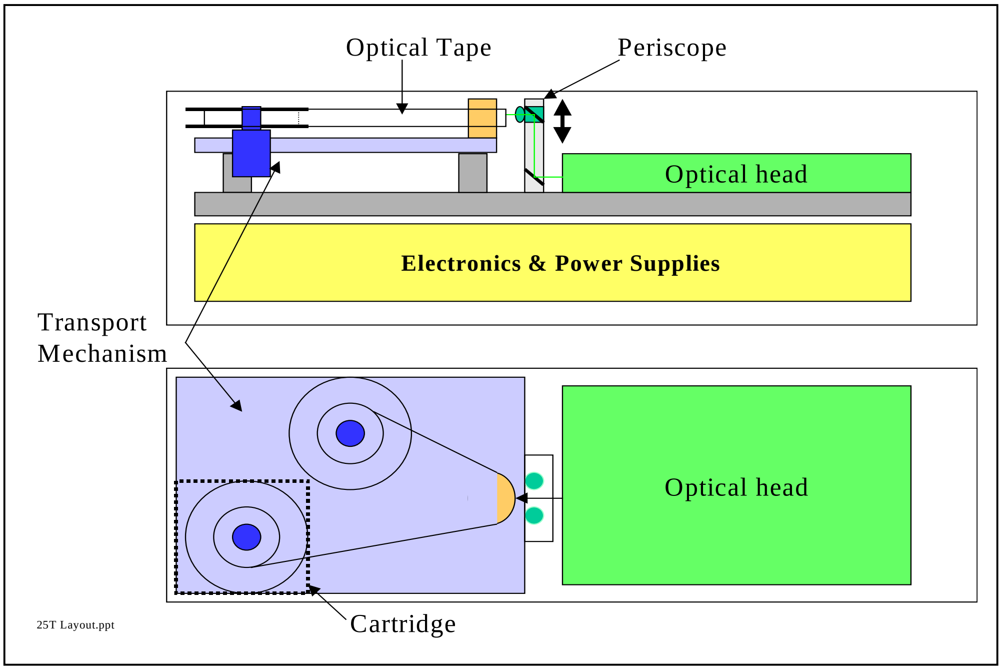


Figure 2 – Optical Tape Drive Layout

Focus of this article is to discuss some intricate design approaches for the optical head.

Optical Head Structure

The optical head is the instrument that writes and reads information onto and from the tape. Its design must support the system level specifications: capacity and data transfer rate. It must also be able to handle tape motion in terms of maintaining tight focus and track servos during record and read back. A simple optics layout is shown in Figure 3.

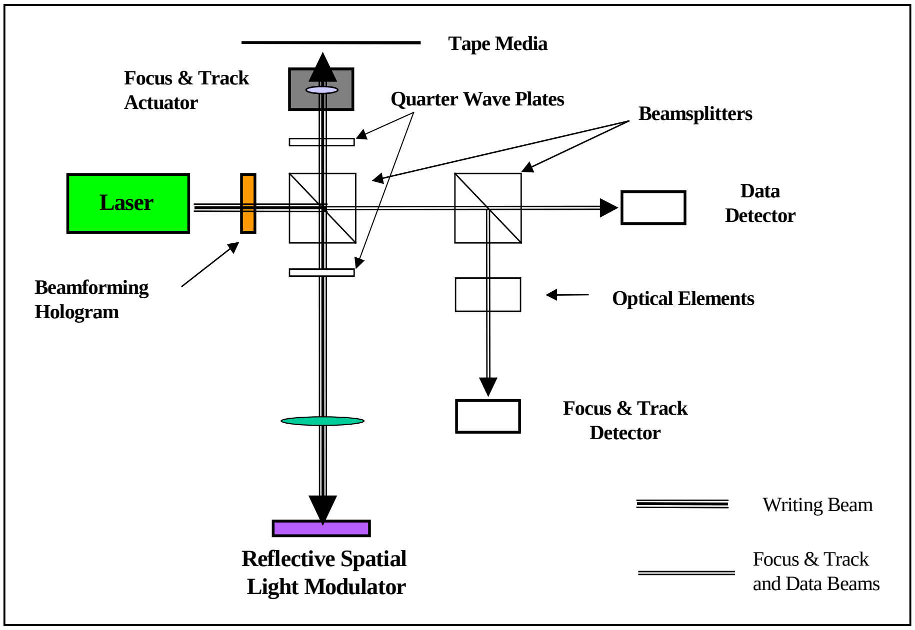


Figure 3 - A simple optics

A single laser is used as the beam source. It is a diode pumped doubled YAG laser generating a beam with a wavelength of 532 nm. The choice of doubled YAG laser, as an added benefit, removes the necessity of a wavelength migration path from a red laser diode to a green or blue laser diode. However, more important than the elimination of the need for a new optical design (due to removal of the wavelength migration path) is avoidance of all the reliability issues and the beam profile variations of a high power laser diode. Figure 4 shows a 200 mW doubled YAG laser used in this design.

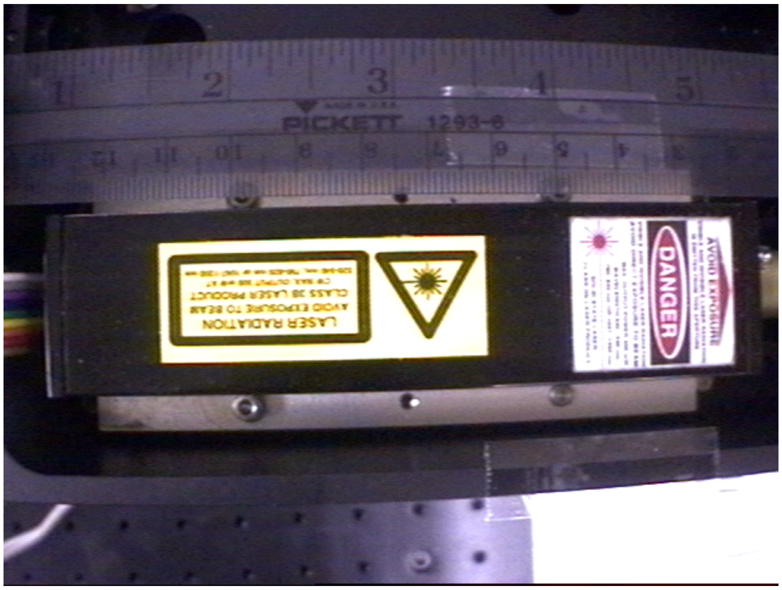


Figure 4 – Doubled Nd:YAG Laser

A 2-dimenational hologram multiplies the single laser beam into an array of collimated beams each of which is capable of read/write operation. Combination of the single laser with a hologram to generate multiple beams increases reliability of the system in contrast to using a 2-dimensional laser diode array. Furthermore, collimation optics design becomes simpler in the former case than the latter case.

The laser beam array after the hologram is imaged onto an electro-optic modulator array, each of which upon activation rotates polarization of the incident laser beam by 90 degrees. Data from the host computer is encoded and fed to the modulator driver. Each laser beam is pulsed according to the streams of ones and zeros that it receives from the electronic write channel. The polarization modulated laser beam array will become intensity modulated after passing through some polarization optics as the beam array reaches the tape plane. The laser beams that are “on” will write mark on the tape, and the beams that are “off” will not.

Figure 5 shows electrical and optical pulses as input and output from a single modulator. The optical pulse rise time shown in the laboratory is about 7 ns, which was limited by the electrical response of the system. Figure 6 shows optical response of four modulators running simultaneously at 12 MHz. The pulses are square shaped and well defined.

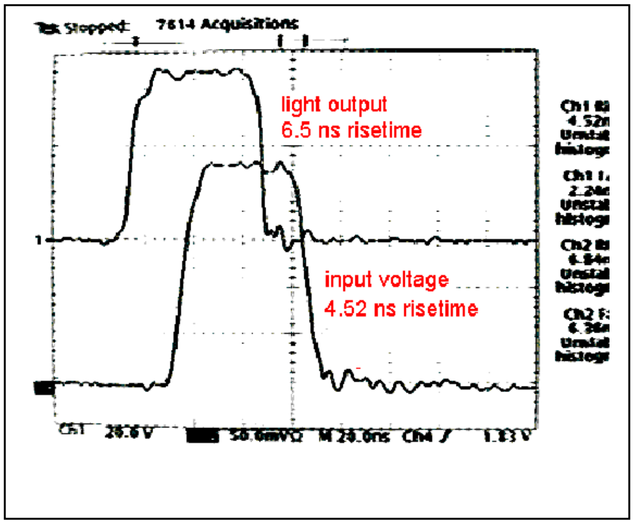


Figure 5 – Voltage Input & Optical Output

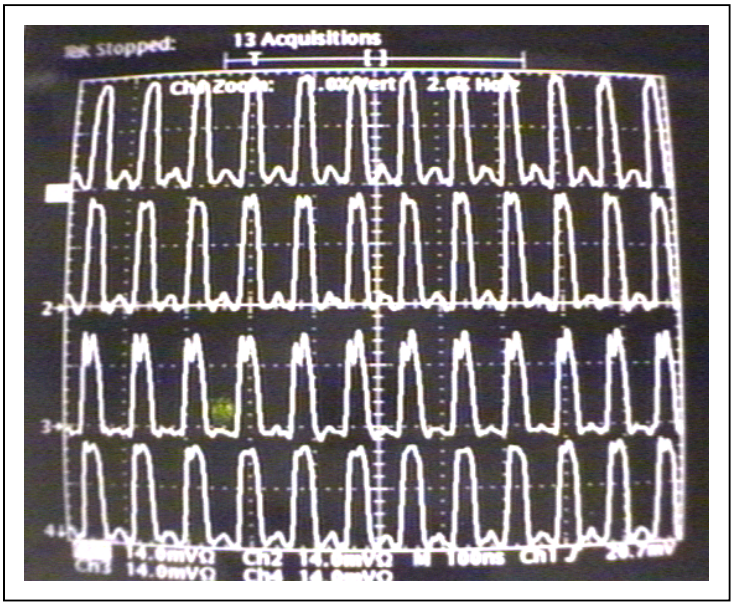


Figure 6 – Optical Pulses at 12 MHz

To decrease access time in traversing width of the tape, the optical head design is split in two parts: fixed optics, and moving optics. The fixed optics consists of the laser, hologram, various passive optics, and detectors. The moving optics is a periscope in effect, which includes a tracking actuator, a focus actuator, and a high NA objective lens. A stepper motor driven carriage that has attached to it the focus and the track actuators traverses width of the tape for various read/write operations. Figure 7 shows the concept of the periscope design.

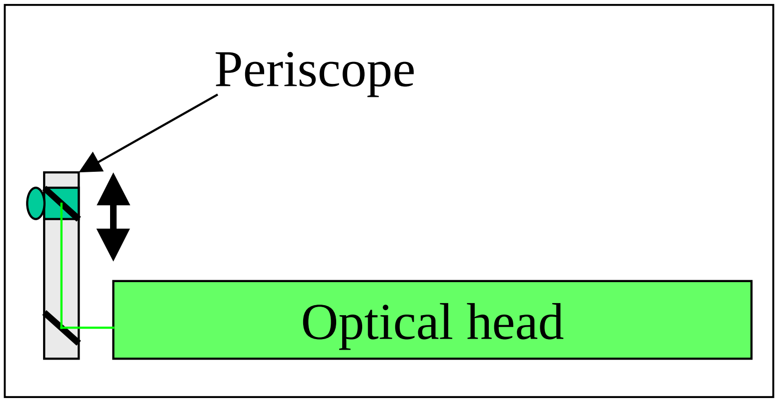


Figure 7 – Periscope Layout

A high bandwidth galvanometer has been designed as the track actuator. As the beam array reflects from the mirror that is attached to the galvanometer, and as the galvanometer rotates about a symmetry axis, the beam array pointing changes; thus, causing a beam displacement at the tape plane. The purpose of the track actuator is to make sure that center of the read beams is always at the center of written tracks.

The focus actuator has a high numerical aperture (NA) objective lens attached. The purpose of the focus actuator is to maintain a minimum spot size at the recording layer of the tape at all times by moving the objective lens along the optic axis relative to the tape plane.

A high NA objective lens has been designed to accommodate a large field. All the beams within the array must be at best focus at the tape plane. In general, a spherical lens forms an image of an extended object on a spherical image plane. Furthermore, as the numerical aperture of the lens increases, the filed flatness of the image plane reduces. However, in our case, the spot array forms a rectangle of dimensions of 6 x 50 μm^2 on the tape surface. The tape thickness is 12.7 µm. Therefore, the aspect ratio of thickness to area necessitates a flat region where the spot array is incident. This issue required us to design a 0.6 NA objective lens that has a flat field up to 1 degrees. Figure 8 shows wavefront error (WFE) data of a fabricated 0.6 NA lens using an off the shelf interferometer.

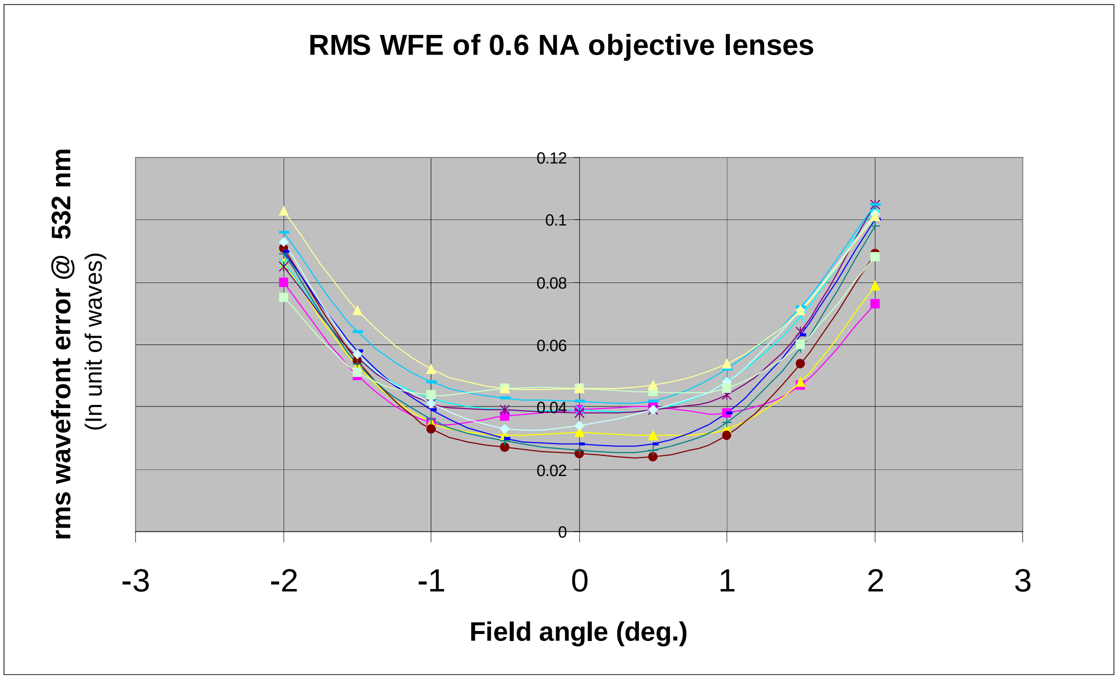


Figure 8 – WFE of the 0.6 NA Objective lens as a function of field angle

Media Structure[1]

The active material is a Kodak proprietary vacuum deposited amorphous thin film of SbSnIn (Antimony, Tin, Indium) alloy. Recording of data is accomplished by heating with a focused laser beam to form sub-micron size crystalline marks. This is possible because the crystallization rate of amorphous SbSnIn alloy thin film depends strongly on temperature. Heating the material to about 250 °C using a focused laser beam causes an instantaneous crystallization while an undisturbed amorphous film stays amorphous almost indefinitely. Figure 9 shows the media structure.

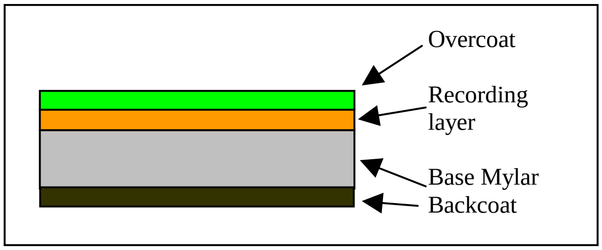


Figure 9 – media structure

The media is very simple in structure. It consists of a Mylar based web sputter coated with the alloy thin film (the recording layer), and then coated with an overcoat for protection of the recording layer. There is a backcoat applied to the other side of the base to avoid electrostatic charge accumulation. Base reflectance of the optical tape is a function of the overcoat thickness. Figure 10 shows the optical tape reflectance as a function of the overcoat thickness for both amorphous and crystalline states.

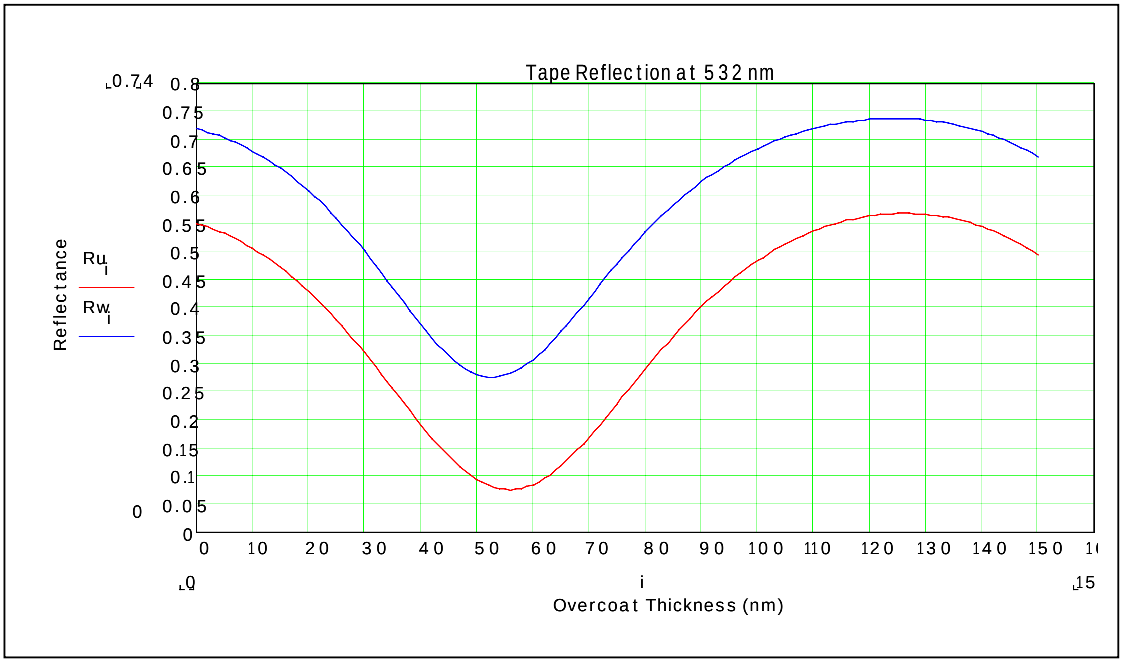
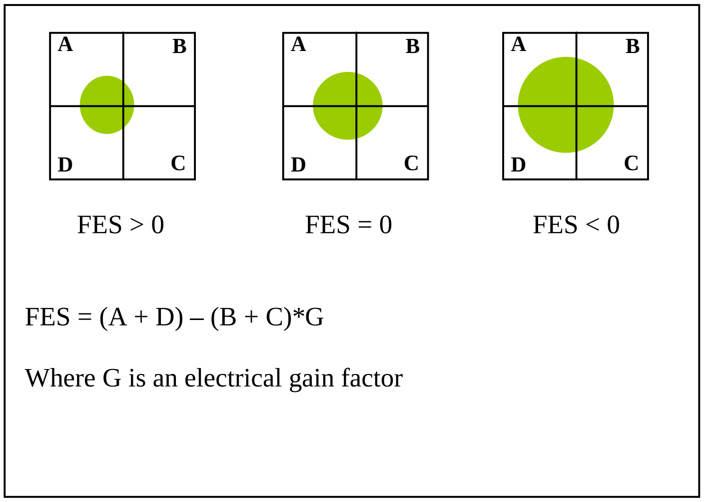


Figure 10 – Tape Reflectance versus Overcoat Thickness at 532 nm

Experimental data

An optically generated error signal controls the distance between the objective lens and the tape plane by moving the focus actuator. Using a modified Wax-Wane method in which the servo beam is offset relative to a bicell, Figure 11, a focus error signal is generated. Size of the servo beam spot at the detector changes as the distance between the tape and the objective lens varies from nominal. It is this size change that is detected, and is converted to an S-curve for focus error detection.



FES = (A + D) – (B + C)*G

Where G is an electrical gain factor

Figure 11 – Modified Wax-Wane schematic

Figure 12a shows the focus S-curve, which has a capture range of 3 µm. Figure 12b shows the residual focus signal while the servo loop is closed with the optical tape running at 10 m/s. As can be calculated, the residual focus error signal is 0.1 µm peak to peak, which is well within depth of focus of the objective lens.

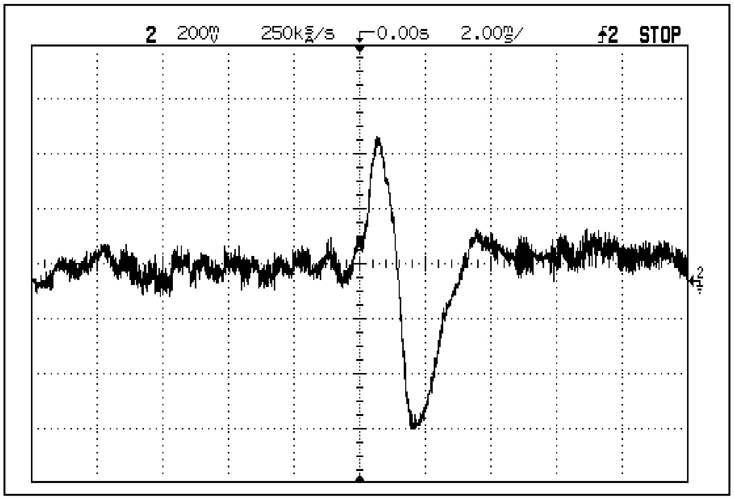


Figure 12a – Focus S-curve

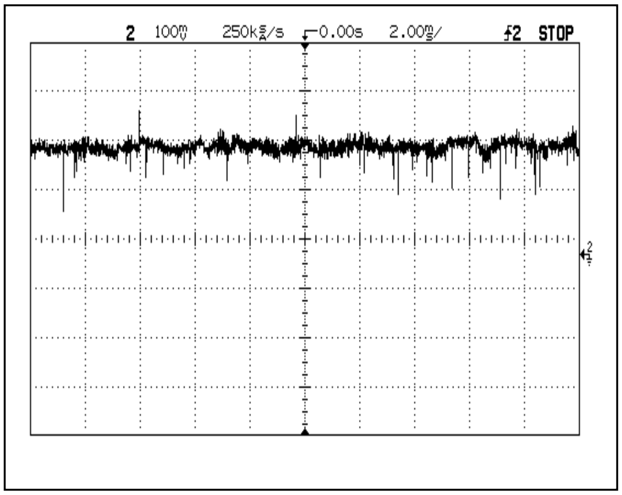
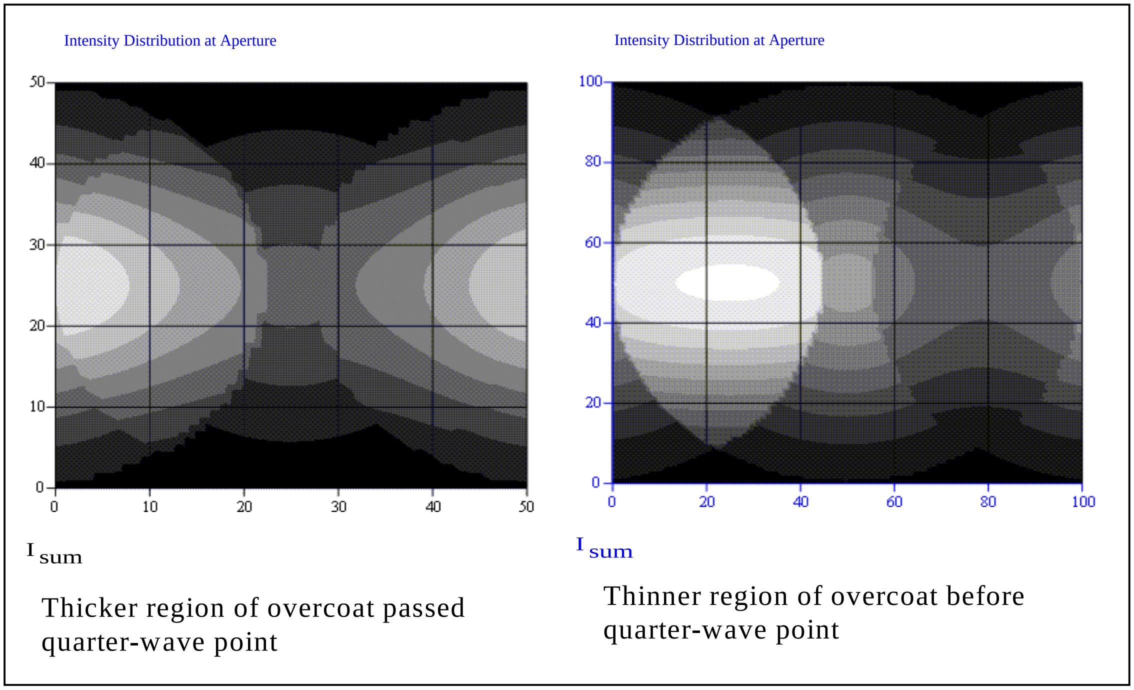


Figure 12b - Residual Focus Signal at 10 m/s

Tracking error signal is generated by using diffraction and interference of coherent light from a grating; otherwise, known as the push/pull method. Since the crystalline structure of the phase change material on the tape has a different complex index of refraction than the amorphous structure, a series of written lines act as a weak phase grating. The tape overcoat can be optimized for maximum push/pull track error signal for a given



Thicker region of overcoat passed quarter-wave point

Thinner region of overcoat before quarter-wave point

Figure 13 – simulation result for push/pull TES versus overcoat

wavelength. Figure 13 shows simulation of intensity distribution of reflected beam from a written tape at the plane of the objective lens aperture. The interference between diffracted orders, 0^{th} and $\pm 1^{st}$, generates bright or dark intensity profiles that when detected properly results in the push-pull tracking error signal. The Figure on the left-hand side shows a weaker contrast than the one on the right hand side indicating a weaker push-pull TES. Table 2 lists the tracking error signal amplitude normalized to the servo sum signal for various tape overcoat thicknesses as measured in the laboratory. The trend found in the simulation is validated by the experimental results.

overcoat Thickness (nm)	NTES (V)
33	4.1
50	4.2
78	0.6
89	0.7

Table 2 – Experimental result for push/pull TES versus overcoat

Figure 14a shows the tracking error signal S-curve derived from four parallel data lines written. The pattern is pseudo random with a maximum frequency of 10 MHz. Figure 14b shows the residual track error signal with both the focus and track loops closed and tape traveling at 10 m/s. The top trace is the residual tracking error signal, and the bottom trace is a data line. In this example, the track spacing is 0.8 um. Therefore, one can calculate the residual error signal to be 0.07 um peak using a sine wave approximation.

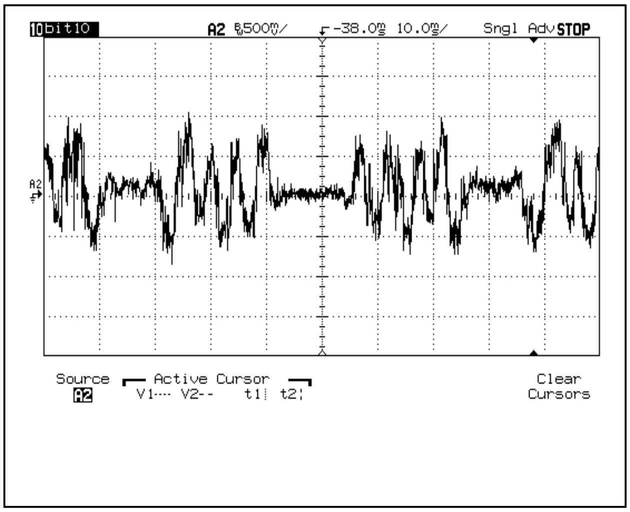


Figure 14a – Track Error Signal from 4 Data Lines

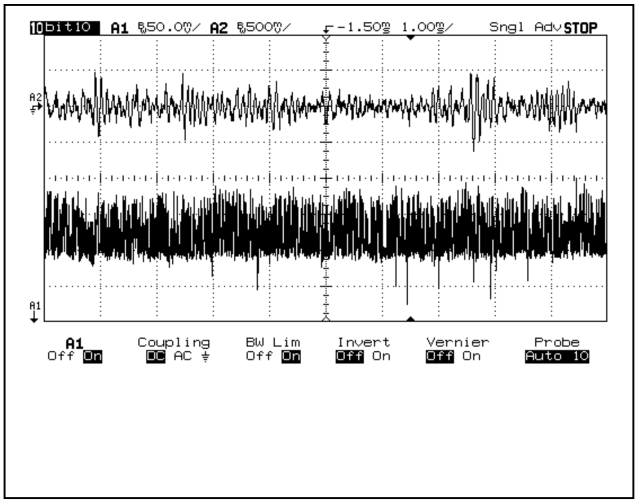


Figure 14b – Residual Tracking Signal

Figure 14c is a magnified version of Figure 14b where individual data marks are shown.

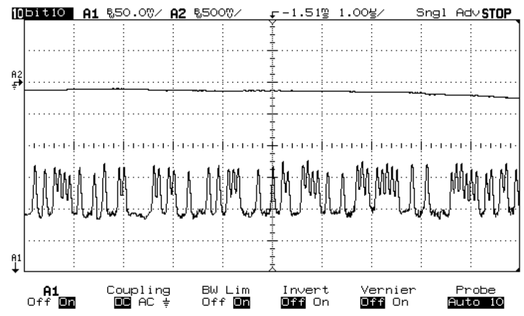


Figure 14c – Magnified version of Figure 14b

As was mentioned before, the writing process takes place by modulating the laser beam array through an electro-optic modulator. Each beam is modulated independent of rest of the array members. To insure proper spacing of the written marks on the tape, the beam array must be skewed relative to the tape direction of motion. For example, if there are m columns and n rows in a beam array, then the array must be tilted by $\tan^{-1}(1/m)$ to insure even spacing among the written tracks. Figure 15 illustrates this point.

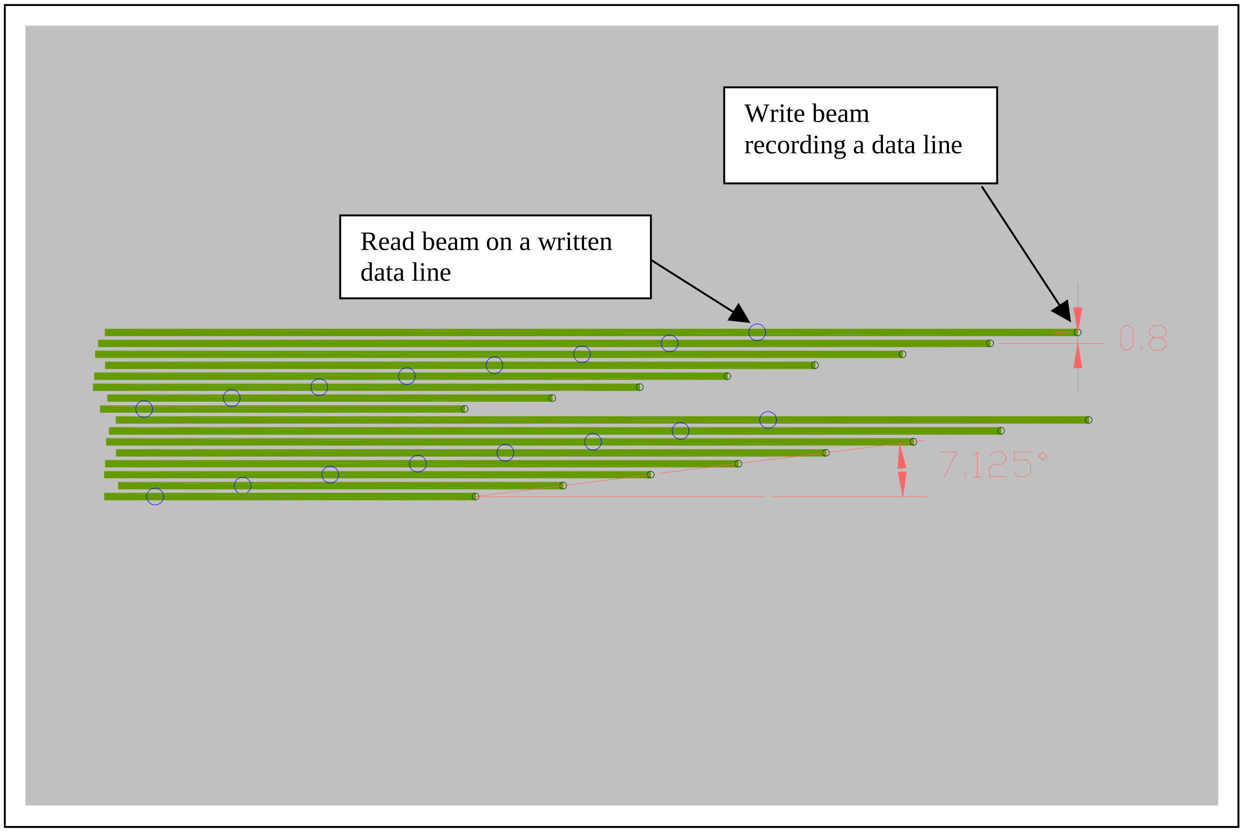


Figure 15 – Beam Array Skew

Although there are many ways of skewing the beam array relative to the tape, in this paper, the optical head was tilted by 7.125 degrees.

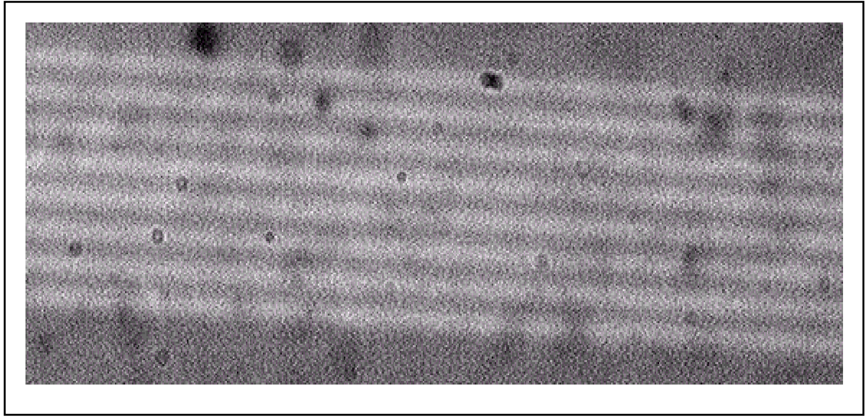


Figure 16 – picture of 8 solid lines written on tape

In one example, 8 solid lines with 0.8 μm spacing were written simultaneously on the tape at 10 m/s, which is shown in Figure 16.

Figure 17a shows many track groups of 4 data lines written on the tape at 10 m/s. The minimum mark spacing is 1 μm and track spacing is 0.8 um in this experiment. Figure 17b is an enlarged photo of a four line simultaneous recording. In this picture the minimum mark spacing is 0.85 µm.

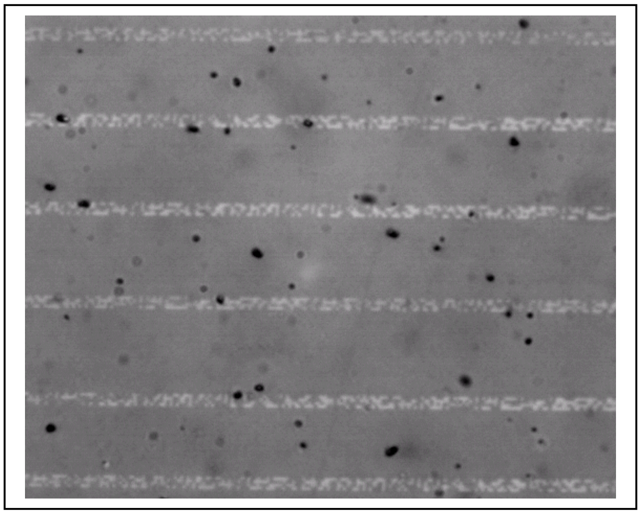


Figure 17a – multiple 4 data lines line at 10 MHz, 10 m/s

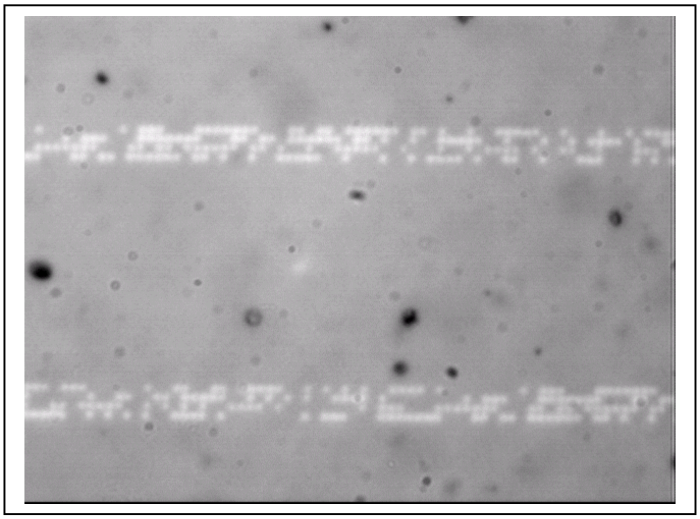


Figure 17b – Magnified version of Figure 16a

Optical resolution simulation is validated by the experimental data as is shown in Figures 18a, b respectively. Optical resolution is defined as the ratio of the amplitudes of the highest spatial frequency signal to the maximum signal amplitude. An optical resolution of 50% was simulated for a perfect system. However, given that the real world is not as perfect and optical aberrations do exist, which degrade the read/write focused spot quality, a measured optical resolution of 40% would be reasonable. Experimental results show an optical resolution of greater than 40%. The upper trace in Figure 18b is the residual track error signal.

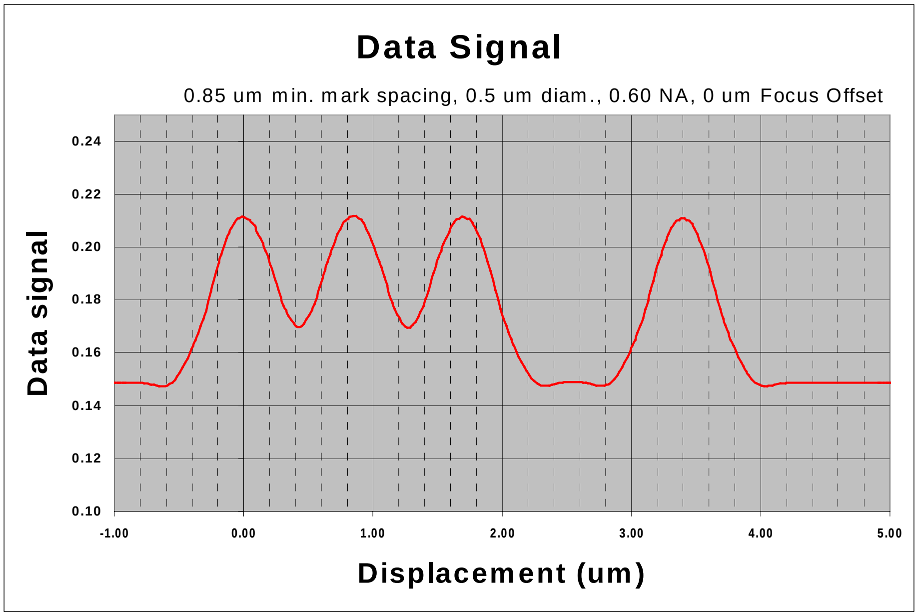


Figure 18a – optical resolution simulation

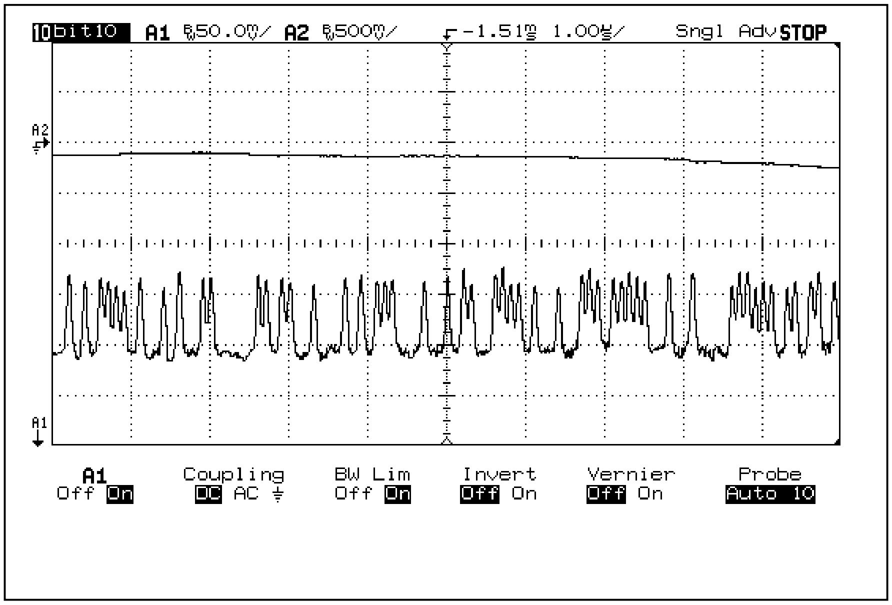


Figure 18b – optical resolution measurement 10 MHz, 10 m/s

Signal to noise ratio (SNR) of the data is shown in Figure 19. A single frequency data pattern at 10 MHz was written on the tape at 10 m/s. Subsequently that data was read back and fed to a signal analyzer. The 10 MHz data peak stands 40 dBs above its base line.

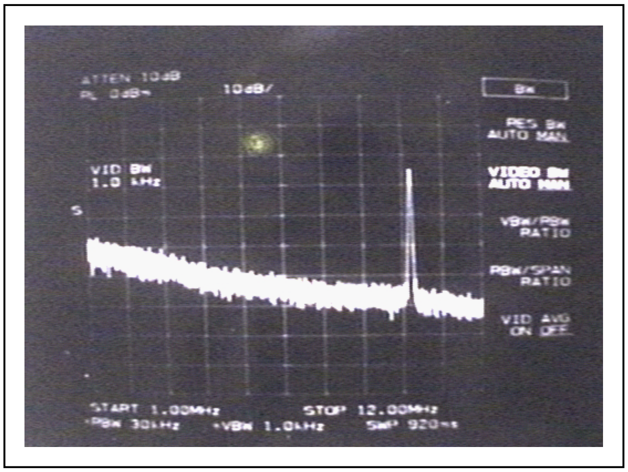


Figure 19 – SNR Measurement of 10 MHz Data

Data track-to-track crosstalk was also both simulated and measured. Simulation result showed that under the worst case situation, the T/T crosstalk is better than 40 dBs down. Preliminary experimental data based on 0.8 um track spacing show similar results.

Figure 20 shows two adjacent data channels one of which is reading data and the other one is on blank tape region. No measurable crosstalk amplitude is noticed. To show that these two channels are indeed adjacent, a region of the tape with a common surface defect with a similar amplitude effect on both channels was chosen. In this way, the defect appears in both adjacent channels and is almost equal in amplitude. However, the data marks do not show up in the adjacent channel indicating lack any noticeable track to track crosstalk.

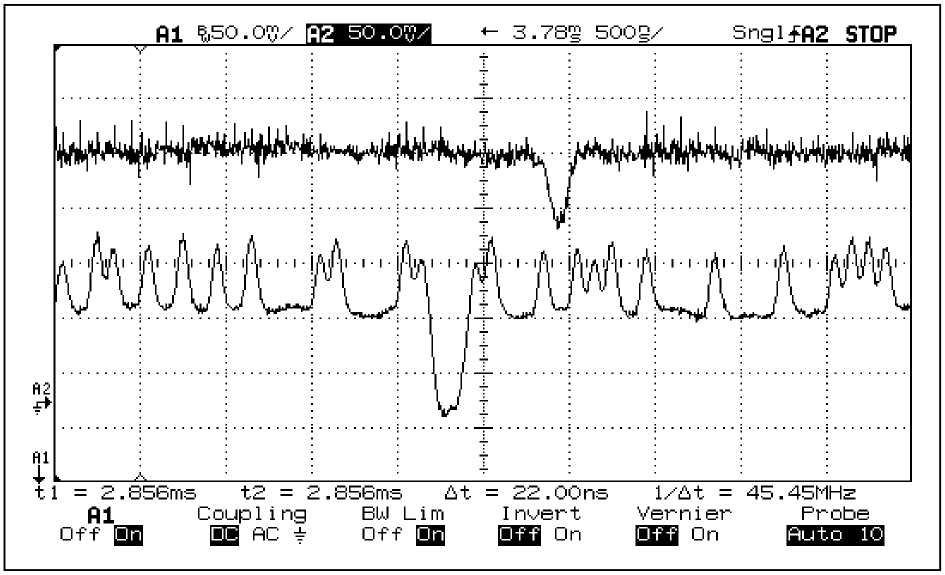


Figure 20 – Track-to-Track Data Crosstalk

Related Work

Other attempts have been made in using a laser diode array to generate the multiple beams to read and write. However, issues of thermal crosstalk, wavelength variation, and beam parameters differences among the individual diodes within the array make the design extremely expensive to manufacture especially when a large number of channels is required for a fast data transfer rate.

Future Work

As media with improved surface quality becomes available, more experiments will be done to gain a better understanding about effects of tape shuttling on data SNR and BER. Furthermore, the capability to record and read back with an increased number of beams will be tested.

Conclusions

In conclusion, we have shown an optical tape drive design capable of storing a nominal 1 TB of user capacity in a 3480-style cartridge with a user data transfer rate of 25 MB/s. We further showed the novel idea of using a single beam and a hologram combination to generate a multiplicity of recording channels. This approach significantly enhances reliability of the tape drive in contrast to using laser diode arrays. This design is extensible to higher data transfer rates with a minimum hardware modification by increasing number of channels. The optical tape drive design approach is very realistic and viable since not only is there no mechanical contact of the tape with either the transport or the optical head, but also the optical tape itself has a lifetime of longer than 30 years. The recorded information will not be damaged by environmental temperature changes or by a strong magnetic field.

References

[1] Tyan et-al. *Kodak Phase Change Media for Optical Tape Applications*. (NASA Conference Publication 3198, Vol. II, September 1992)