Optical Data Storage

Optical data storage is found in popular consumer products. Compact Discs (CDs), Digital Versatile Discs (DVDs), and MiniDiscs (MDs), are all forms of optical data storage. More advanced forms of optical data storage include high-speed devices and library products. All optical data storage devices use optical principles to achieve high data density, rugged packaging, reliable information retrieval, and cost-effective production.

In general, optical data storage relates to placing information on a surface so that, when a light beam scans the surface, the reflected light can be used to recover the information. There are many forms of optical storage media and many types of optical systems used to scan data. This chapter discusses the basic principles of optical data storage, types of commercial optical media available in 2002, several performance parameters and some interesting prospects for future systems.

1.0 Inspiration for the Invention

The optical disk was envisioned in 1958 by an eclectic engineer named David Paul Gregg, who patented the idea in 1961.[1,2,3] At the time, magnetic disks were in their infancy, and there was no low-cost "videodisk" system that could be marketed as a consumer product. As told by the inventor, inspiration for the videodisk system came from the picture shown in Fig. 1, which is a photograph from a trade magazine in the mid 1950's. The photograph was produced from an early scanning electron microscope. The narrow lines in the lower-left corner of the picture, which were written by the electron beam, are 0.030 micrometer wide and are separated by 0.070 micrometer.[1] Gregg saw the picture and, while on horseback in Mexico, imagined a rotating plastic disk with tracks of data marks read by an inexpensive optical system. As originally envisioned, a master disk is first written with an electron beam. The master disk is used to produce low-cost replicas, which are then sold to consumers.

In many ways, Gregg was prophetic. The CD, a mature development and improvement of Gregg's invention, is an immensely successful consumer product. DVD systems are advanced versions of CDs. Today's most advanced systems, which use blue laser diode optical systems, often utilize electron-beam machines to make master disks. Someday, it may be possible to record information with the 30 nm linewidth observed in Fig. 1, which would result in a disk with data density several thousand times the data density found on DVDs.

2.0 Data Marks and Spaces: The Information Carriers

Digital information [xref?] is stored on optical disks in the form of arrangements of data marks in spiral tracks. Small sections of CD and DVD surfaces are illustrated in Fig. 2, which also displays representations of laser spots that are focused on the surfaces to write and read data. CDs typically use 1.6 micrometer track pitch, which is the radial distance between turns of the spiral tracks. Data marks are nearly one-half as wide as the track pitch. Lengths of data marks

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[1] For a sense of reference, if we were to magnify a 1.0 micrometer wide line to the length one yard, edge thickness of a piece of paper under the same magnification would be about the length of a football field. The lines in Fig. 1 would be about one inch wide. (1 micrometer = 10^{-6}m = 0.000039 in)

and spacings between marks are determined by the encoding scheme [4,5] used to translate user data into mark patterns along each track, which is described in more detail in Section 5.8. Width of the CD laser spot is slightly smaller than the track pitch. DVD media are similar to CD media, except track pitch is smaller (0.74 micrometers), data marks are shorter and narrower, and the laser spot diameter s is smaller. Since there are more data marks per unit area on a DVD compared to a CD, the DVD can hold more data.

3.0 Optical Data Storage Principles

Storage and retrieval of data on optical disks can be described in two simple steps. First, data marks are recorded on a surface. Data marks can be prerecorded, like on a music CD, or they can be recorded by users on blank disks, like with CD-recordable products. The second step is retrieval of information from the disk, where a light beam scans the surface. Modulation in the reflected light is used to detect the data-mark pattern under the scanning spot.

The process for exposing data marks on a recordable optical disk is shown in Fig. 3, where an input stream of digital information is converted with an encoder and modulator into a drive signal for a laser source. The laser source emits an intense light beam that is directed and focused onto the surface with illumination optics. As the surface moves under the scanning spot, energy from the intense scan spot is absorbed, and a small, localized region heats up. The surface, under the influence of heat beyond a critical writing threshold, changes its reflective properties. Modulation of the intense light beam is synchronous with the drive signal, so a circular track of data marks is formed as the surface rotates. The scan spot is moved slightly as the surface rotates to allow another track to be written on new media during the next revolution.

Data marks on prerecorded disks are fabricated by first making a master disk with the appropriate data-mark pattern. Masters for prerecorded CDs and DVDs are often exposed in a similar manner to exposing data marks on recordable optical disks, except that the light-sensitive layer is designed to produce pits in the master that serve as data marks in the replicas. Inexpensive replicas of the master are made with injection-molding equipment.

Readout of data marks on the disk is illustrated in Fig. 4, where the laser is used at a constant output power level that does not heat the data surface beyond its thermal writing threshold. The laser beam is directed through a beam splitter into the illumination optics, where the beam is focused onto the surface. As the data marks to be read pass under the scan spot, the reflected light is modulated. Modulated light is collected by illumination optics and directed by the beam splitter to servo and data optics, which converge the light onto detectors. The detectors change light modulation into current modulation that is amplified and decoded to produce the output data stream.

4.0 Commercial media

There are several types of optical disks, which can be differentiated by the type of data marks on the recording layer. The most popular disks are based on pit-type, magneto-optic, phase-change and dye-polymer data mark technologies. Several commercial trade names are associated with the four technologies, as shown in Table I. In this section, basic data-mark technologies are reviewed, and commercial formats are listed.

Pit-type data mark technology for CD-read-only-memory (ROM) and DVD-ROM products is based on a very simple scattering phenomenon. Most CDs, like music and data distribution CDs, are ROM disks. The small data-mark pits are arranged in spiral tracks around the center of the disk, as shown in Fig. 2. The pit lengths are about one micrometer to three micrometers long. The widths of the pits along a track are nearly uniform and measure about one-half to eight-tenths of a micrometer. As the light spot passes over a pit, most of the reflected light scatters away from the illumination optics. The remaining light collected by the objective lens is small compared to the amount of light that gets collected when the spot is over a smooth portion of the track, where the disk surface acts as a mirror to the focused light. The data signal is derived from the detector that senses the amount of collected light, as shown in Fig. 4.

The amount of light scattered from each pit depends on the depth of the pit and the size of the laser beam illuminating it. A simplistic explanation is that the portion of the laser spot reflected from the pit exhibits a phase change due to the additional path that the light must traverse compared to the portion of the laser spot that is reflected from the surrounding flat area of the recording surface. The two portions of the spot interfere destructively [xref:?] upon propagation of the light back to the objective lens if the effective depth of the pit is one-eighth of the illuminating laser wavelength. In practice, the pit depth profile is designed to not only provide good data signal modulation, but also good tracking performance, as explained in Section 5.6, which is optimized at a slightly different pit depth.[6]

In order to increase the amount of light reflected to the detector, the entire recording surface of the CD, including both pits and areas between pits, is coated with aluminum. The aluminum is then coated with a lacquer or other protective layer, onto which the label is printed. The read out optical system focuses light through the clear surface of the disk, as shown Fig. 5, so the data mark patterns and track are actually located nearer the label than the clear side through which the user views the rainbow diffraction pattern [xref:] that forms due to the close radial spacing of the tracks. The plastic CD substrate is 1.2 mm thick, which is designed so that contamination, like fingerprints or scratches, on the surface of the disk does not adversely affect disk performance during read out.[7] DVD substrates are only 0.6 mm thick, which implies that DVDs may be more sensitive to contamination than CDs.

Dye-polymer or dye-monomer technology is used in CD-R products. Dye polymers/monomers are organic films that are ablated to form pits along tracks.[8, 9, 10] To form a pit, a high-power focused spot locally heats a micron-sized area. The dye polymer absorbs a large percentage of the laser energy. Due to the low thermal conductivity of dye polymers, extremely high temperatures can be reached. Although the exact mechanism of pit formation in CD-R is not known, a simple explanation is that, in the heated area, the dye material is vaporized or heated to the point that material flows to form a pit. To read data, a low-power laser beam scans the track, and the collected light is sensed with a simple detector. The collected light is modulated by light scattering, which is similar to the phenomenon described above for pit-type media. Since the recording process for CD-R's is destructive, the user can only write data marks once. Data marks cannot be erased and rewritten.

There are three classifications of dyes used to make CD-Rs, which are cyanine, metallized azo, and phthalocyanine. At a laser wavelength to 0.78 micrometers, where CD players are designed to operate, there are only slight differences in performance between the dyes during the writing process. All the dyes absorb laser light and heat the recording surface. In addition to the dye layer, CD-Rs have a reflective layer, like the CD-ROM. However, the reflective layer is usually silver or gold instead of aluminum.

Different combinations of dyes and reflective layers influence visual appearance of the CD when viewed from the clear side of the substrate. Since the visible spectrum [xref:] is shorter wavelength than the recording laser wavelength for CDs, the dye usually appears with a characteristic semitransparent color. The reflective layer appears either silver or gold. Table II lists some combinations of dyes, reflectors, and the resulting synthesized color to the eye. For example, the green CD-R, the cheapest of combination, uses the cyanine dye.[11] By itself, the cyanine dye is blue in color, but, together with the gold reflector, the recording surface appears green. Cyanine's ability to maintain reflectivity is poor, which gives it an expected lifetime of only about 10 years. Improved-formula cyanine dyes in combination with silver reflectors (blue synthesized color) have shown better performance, which is better than twenty-year lifetime after recording. The gold-colored CD-R uses a phthalocyanine dye and a gold reflector. The dye is transparent by itself, so the gold color shines through. Modulation in the reflected light caused by writing on the gold medium is the best of all CD-R media, and lifetime of such CD-R's is said to be over 100 years.[12] Blue media are made of azo dyes. Like cyanine, the azo dye is blue, but azo disks use a silver reflector, which result in a blue synthesized color.

CD-RW products use a different recording layer material than CD-R's. In addition to allowing the user to write data marks, data marks can also be erased with multiple cycles before degradation. CD-RW's use phase-change technology, which is based on differences of the crystalline and amorphous states of semi-metal alloys, like AgInSbTe or GeSbTe.[13, 14, 15] To record or erase phase-change data marks, a high-power focused spot locally melts the medium in micron-sized regions as the disk spins. The thermal cycle of the local regions determines if the region will stabilize in a crystalline or amorphous state. By controlling the energy in the focused spot, the thermal cycle and the state of the material can be controlled. For example, a high power laser pulse and rapid cooling quenches the material into the amorphous state, as shown in Fig. 6 when the laser is pulsed to the peak power level. A lower-power laser beam and slow cooling anneals the material into a crystalline state. Usually, marks are in the amorphous state and the background is in the crystalline state. CD-RW media is a "write dark" media, which means that the amorphous state of the data marks does not reflect as much light as the crystalline background. Some commercial media are "write bright", in that the recording layer is initially in the amorphous state, and bright crystalline marks are written on the dark amorphous background.[16] In Fig. 6(a), a virgin track is exposed to a certain mark pattern. Three clearly defined, dark amorphous marks are formed along the track, where one each data mark corresponds to a peak-power laser pulse. The bias power ensures that regions between marks anneal into the high-reflectivity crystalline state. When new data are written on the track, as shown in Fig. 6(b), a similar sequence of laser pulses are used, except that the laser pulses correspond to the new data-mark pattern. Old data marks are overwritten and replaced with either crystalline or amorphous material of the new pattern. The phase-change process inevitably involves a mechanical deformation of the material. Therefore, the number of direct overwrite cycles is limited to several thousand. Like a CD player, the detector in a CD-RW player simply senses the amount of collected light. The data signal is derived from the detector current.

The readout signal contrast is optimized in a CD-RW player by adding several thin-film layers around the recording material. The effect of the layers is to produce a thin-film reflective filter [xref:?]. A typical configuration of the storage layers in CD-RW products is shown in Fig. 7. The laser beam focuses through the clear substrate material and into the thin-film recording layers. The first layer is a transparent dielectric. The second layer is the recording material, and the third layer is another layer of transparent dielectric. The fourth layer is a reflector. The thicknesses of these four layers are designed to tune the reflective properties for maximum signal contrast, and they are also adjusted to provide adequate absorption so that a reasonable amount of laser power can be used for writing.[17] A protective coating and a label and ink layer separate the thin films from the environment.

Magneto-optic (MO) products store information in small magnetic data marks, which are about the same size as pits on a CD. The recording layer is initially erased so that all magnetic domains are aligned in one direction perpendicular to the recording surface, as shown in Fig. 8(a). In this configuration, the magnetic domains are extremely stable. A large magnetic field of several thousand oresteds [xref:?] is required to overcome the magnetic moment of the domains. The magnetic field required to reorient domains is called the coercivity.[xref:?][18] To record data marks, a high-power focused spot is used to locally heat the recording surface. Heat reduces coercivity, so magnetic domains in the region of the focus spot can be reoriented with an external magnetic field. When the laser beam is switched to low power between data marks, the recording layer is not heated, and the eternal magnetic field has no effect on domain orientation.

As described in Fig. 3, the laser beam is modulated between high power and low power as the disk spins in order to write a pattern of data marks along each track. Each mark contains magnetic domains oriented in the opposite direction compared to the magnetic domains of the background.[19] The marks have the property that, as a low-power focused light spot passes over it, polarization [xref: polarization] of the reflected light is rotated, as shown in Fig. 8(b). Polarization rotation on reflection is due to the polar Kerr effect.[20] When the laser beam illuminates a data mark with domains oriented away from the laser beam, linear incident polarization is rotated slightly in the counter-clockwise direction. When the laser beam illuminates the region between data marks, linear incident polarization is rotated slightly in the clockwise direction. In order to detect the data signal, a detector is used to sense change in polarization of the reflected light. For example, an indication that the reflected light is rotated in the counter-clockwise direction implies that the laser spot illuminates a data mark. In order to erase data, the external magnetic field in Fig. 8(a) is reversed, and the laser beam heats an entire section of the track. A major difference between CD and MO products is that the MO marks are produced in a track with an almost undetectable change in the topology of the track. That is, there is almost no mechanical deformation of the track as the marks are recorded or erased. This property enables MO products to exhibit over one million erase cycles with little if any degradation in performance.[21, 22]

A collection of the available CD and CD-like formats are listed in Table III, along with their associated data-mark technology.[23] DVDs used for movie or data distribution are pit-type ROM disks. The tack pitch and pit size is smaller than in CDs, as shown in Fig. 2. DVD products can also be erasable, and there are a multitude of formats available, as listed in Table

IV. These products use erasable-change technology. DVD-R products, like CD-R, use a write-once dye polymer recording layer. Unlike CDs, DVDs can use more than one storage layer per disk. DVDs can be double sided, use two layers on one side, or use two layers on each side. Adding layers increases the total capacity of the disk.

5.0 Technology

Several important aspects of optical data storage technology are associated with the optical-mechanical-electrical system that is used to write and read data to the disk. This section reviews basic concepts necessary to understand how these systems work.

5.1 Data density and spot size

Capacity of an optical disk is determined by its *data density*, which is the number of bits of information stored per unit area on the surface, and the recording area. Data density is often specified in gigabits (10^9 bits) per square inch of recording surface area (Gb-in^{-2}). For example, a 0.65 gigabyte (GB) CD has a recording area of about 14.5 square inches, so the data density is $(0.65)(8)/14.5 = 0.36$Gb-in^{-2}, where one byte = 8 bits.

A fundamental limitation to the data density is due to the size of the focused laser beam that illuminates the surface. Figure 7 shows a detailed picture of the laser irradiance approaching the surface, where irradiance is defined as the laser power per unit area. Ideally, maximum irradiance is located at the recording material, along with the smallest spot size s. As the distance increases away from the ideal focus, the spot size increases and the peak irradiance decreases. A defocus distance Δz of only 3 micrometers dramatically reduces peak irradiance and increases spot size. An approximate formula used to estimate the ideal spot size is $s = \lambda/(\sin\theta)$, where θ is the marginal ray angle of the illumination optics, as shown in Fig. 3. Spot size s is the full width of the irradiance distribution at the $1/e^2$ (13.5%) irradiance level relative to the peak. The value of $\sin\theta$ is often called the *numerical aperture* or *NA* of the optical system.[xref:?] CD systems exhibit $\lambda = 0.78$ micrometers and $NA = 0.47$, which produce a spot size of 1.7 micrometers. DVD systems exhibit $\lambda = 0.65$ micrometers and $NA = 0.60$, which produce a spot size of 1.1 micrometers.

5.2 Thermal recording

In order to write data onto the spinning disk, the laser must be pulsed to a high power level. The time duration of the high-power pulse determines the length of the data mark that is written onto the surface. Laser writing is possible because the medium is thermally sensitive. That is, the medium exhibits a thermal threshold.[8] Below the threshold, medium properties do not change significantly. Above the threshold, a physical change occurs in the medium.

Figure 9 shows lines of constant temperature, which are called *isotherms*, generated on an aluminum surface for a 200 nano-second (200×10^{-9} sec) focused laser pulse. The surface is moving at 10 meters per second, so the isotherms are spread out along the scan direction. This profile is representative of those found in DVD optical disks. Notice that the end of the pulse generates a wider isotherm than at the beginning of the pulse, due to the fact that heat builds up and spreads out in the direction perpendicular to the scan. This effect is called *thermal blooming*, and is a serious problem, especially in mageto-optic systems, if not corrected by varying the properties of the laser pulse.[24] Fig. 9 indicates that, if the threshold temperature of the medium is equal to the 200° C isotherm, a data mark of approximately 0.6 micrometers wide and 2.5 micrometers long will be written at this location on the surface of the disk.

5.3 Frequency response and equalization

The ultimate limit to the size of the data marks on the recording surface is determined by the frequency response of the optical system. *Spatial frequency* is 1/T, where T is the period of the data-mark pattern. As the period decreases, spatial frequency increases. The frequency response can be understood simply by recognizing the behavior of the reflected light and how the reflected light is collected by the objective lens. For example, Fig. 10 shows the reflected light distribution for a periodic pattern of data marks along a track. The reflected light consists of three cones. The direct reflection is the central cone. The two outer cones are called *diffracted orders*. They are very similar to the central cone in appearance, but they are spread apart by angle ψ. As T decreases, ψ increases, and the diffracted orders spread more widely apart. ψ is also inversely proportional to the laser wavelength. Shorter-wavelength lasers exhibit smaller ψ.

When the spot scans over data marks, the optical phase of each diffracted order changes, but the phase of the central cone does not change. The phase difference between the diffracted orders and the central cone produces a modulation in the overlap area due to interference. That is, as the spot scans over data marks, the overlap areas get brighter and darker as a function of the relative position between the spot and each mark. Brightness of the central cone does not vary. Therefore, the contrast of the signal modulation received at the detectors is determined by the amount of overlap area. More overlap area produces a higher contrast data signal. As T decreases, so does the overlap area. At some critical mark period, there is no overlap and, consequently, no signal modulation at the detector. This critical mark period is called the *resolution limit* T_R of the optical system. A numerical value for T_R is found from

$$T_R = \frac{\lambda}{2NA} = \frac{s}{2} \quad ,$$

where NA is the numerical aperture of the objective lens and s is the spot size.

Figure 11 shows the *modulation transfer function* for the optical system,[xref:?] which plots the contrast of the current signal modulation versus the spatial frequency of the data-mark pattern. Maximum modulation is observed for long marks. The contrast reduces gradually to the resolution limit. The maximum mark frequency in practical devices is well above the resolution limit. For example, the shortest mark period in CDs is about 1.8 micrometers, which is about a factor of two longer than the resolution limit of 0.85 micrometers. Of course, real data patterns are more complicated than simple periodic patterns, but each real data pattern can be decomposed into a collection of weighted periodic patterns. Therefore, the modulation transfer function is also useful in describing system behavior for real data patterns.

When the real data pattern contains both high-frequency and low-frequency components, a significant contrast difference exists in the current signal. These differences in contrast make detecting signal transitions difficult. In order to minimize the contrast difference, electronic circuits are often employed during signal amplification, as shown in Fig. 4. The electronic circuits partially *equalize* the modulation transfer function and provide more reliable signal decoding.[25] An example of an equalized modulation transfer function is shown in Fig. 11, where the high-frequency contrast is boosted with respect to the low-frequency contrast. Unfortunately, physical limitations of electronic circuitry and noise considerations do not permit ideal equalization, which would exhibit uniform contrast for all spatial frequencies out to the resolution limit.

5.4 Effects of defocus

An example of the effects of defocus is shown in Fig. 12, where irradiance of a DVD-like system with NA = 0.6 and $\lambda = 0.65$ micrometers is plotted for several values of Δz. In focus at $\Delta z = 0$, the spot is well confined and only a small fraction of the spot energy is contained in the diffraction rings surrounding the central lobe. At $\Delta z = 0.5$ micrometers, the peak irradiance has reduced slightly and a small amount of energy has shifted to the first diffraction ring closest to the central lobe. At $\Delta z = 0.5$ micrometers, changes in the spot shape will not dramatically affect device performance. However, as defocus increases beyond $\Delta z = 0.5$ micrometers, peak irradiance degrades rapidly and a significant amount of energy is spread into the diffraction rings. An estimate of the allowable *depth of focus* is $\Delta z = +/- \lambda n/(4 \sin^2 \theta) = +/- \lambda n/(4\mathrm{NA}^2)$, where n is the refractive index of the disk substrate.[xref:?] For example, with $n = 1.5$, $\Delta z = +/-$

0.67 micrometers. The effect of defocus on an unequalized modulation transfer function is shown in Fig. 11, where the mid-frequency response of the system suffers severe degradation.

5.5 Servo optics

The size of the focused spot is very small in the direction along the tracks, which allows many data marks to be written for each revolution of the disk. Since the light spot is also small in the direction perpendicular to the track, tracks can be spaced closely together. In CD systems, track pitch, where pitch is defined as the center-to-center track spacing in the radial direction, is typically 1.6 micrometers. In DVD systems, track pitch is 0.74 micrometers. Data-mark width is typically less than one half the track pitch in order to reduce the effects of crosstalk from marks on adjacent tracks. The optical spot must be centered over the marks as the disk spins in order to obtain maximum signal amplitude at the decoding electronics. A typical requirement is that the spot must be kept on track center to better than one-tenth the track pitch, or 0.16 micrometers for CD systems and 0.07 microns for DVD systems. In the focus direction, the spot must be controlled to better than one-tenth the depth of focus, which is about 0.25 micrometers for CDs and 0.13 micrometers for DVDs.[26, 27]

This demanding control of the spot center and focus position is complicated by the fact that the optical disk and the electric motor that rotates the disk suffer from loose tolerances that induce large variations in the track position as the disk spins.[28] For example, thickness of CDs can vary by more than 50 micrometers. Registration errors during the molding process can offset the center of the track radii by more than 30 micrometers from the center of the disk rotation. Wobble of the motor shaft can induce variations in the focus position by several hundred micrometers.

In commercial optical data storage systems, position control is accomplished with closed-loop feedback servos. A basic diagram that illustrates the servo technique is shown in Fig. 13. The difference between the desired spot position and an error signal that is derived from the actual spot position is amplified with some gain G and used as input to an actuator H.[29] The actuator is usually a mechanical device, like a voice coil, which moves an optical element that, in turn, repositions the spot in either the focus direction or across the tracks. The spot position is instantly determined by the feedback sensor, and the new information is fed back into the control loop.

Both focus and tracking actuators are usually combined into one mechanical unit that moves the objective lens. A photograph of an actuator assembly from a commercial CD player is shown in Fig. 14. The objective lens is mounted in a suspension that has a range of motion of a few millimeters in both the focus and tracking directions. The flexure of the suspension is very stiff with respect to motion in any other direction. The fixed part of the suspension also has permanent magnets mounted on it that are aligned with electric coils on the moving part of the actuator assembly. As electric current is passed through the coils, the induced magnetic field presents a force on the permanent magnets and moves the suspension. If the tracking coils are activated, the suspension moves in the cross-track direction. If the focus coils are activated, the suspension moves in the focus direction. By moving the suspended objective lens, position of the focus spot on the disk can be changed. When the actuators are combined with a servo loop, accurate control of the spot position is possible, even in extreme environments like those found in portable disk players.

5.6 Feedback sensors

An important part of the servo loop pictured in Fig. 13 is the feedback sensor. In fact, it is not possible to control the spot position better than the sensor can detect position errors. Usually, separate tracking and focus sensors are implemented in optical data storage devices. The error signal generated from the tracking sensor is called the *tracking error signal* (TES), and the error signal generated from the focus sensor is called the *focus error signal* (FES).[7] The following TES and FES sensors are described:

Push-pull tracking	is a method to provide a tracking error signal using a groove pattern on the disk, where the period of the grooves is equal to the track pitch.
Three-spot tracking	is a method to provide a tracking error signal by detecting the signals from three spots focused onto the disk, where the central spot is centered over a track and two neighboring spots are slightly each side of the central spot in the direction across the track.
Astigmatic focusing	is a method to provide a focus error signal by fabricating a small amount of astigmatism into the servo optics.

Generation of a TES signal using grooves is shown in Fig. 15. In addition to the data marks, each track contains a land and groove area. Data marks are usually written in the land areas, which are closer to the objective lens than the grooves. The collection of lands and grooves forms a diffraction grating in the cross-track direction. Like with single-frequency data-mark patterns, the land/groove diffraction grating produces separated cones in the reflected light due to diffraction. When the spot is centered on the groove, the phase of each diffracted order is equal, so the overlap areas are of equal brightness. When the spot is off center, the phase of the diffracted orders change, and brightness of the overlap regions become unbalanced. This brightness asymmetry is detected with a split-cell detector. Current signals A and B are subtracted to form the TES. When the spot moves in one direction off center, the total power on detector A becomes brighter than the total power on detector B. The TES signal is positive. As the spot continues to move in the same direction, the detector signals become more unbalanced, which creates a more positive TES. If the spot moves in the opposite direction, the detectors become unbalanced in the opposite sense, which creates a negative TES. Near the center of the track, the TES is linear and provides a good quality feedback signal that is directly proportional to the position error. The TES is periodic with a period equal to the track pitch. This type of TES signal is called *push-pull tracking*, which is descriptive of the light-pattern behavior on the detectors as the spot moves off track center.[30] Push-pull tracking is often used in CD-R and CD-RW players, where some form of tracking reference is necessary before data can be written.

Both regular data-mark patterns and grooves produce diffracted orders in the reflected light. These orders overlap at the objective lens, as shown in Fig. 16. Diffracted orders from the data-mark patterns spread in the direction parallel to the scan direction, and the amount of spread is proportional to the data-mark frequency. Diffracted orders from the grooves spread in the direction perpendicular to the scan direction, and their separation is constant. Modulation is observed in the overlap areas between the data-mark orders and the objective lens as the spot scans along the track. In addition to the modulation due to the data pattern, brightness changes can be observed in the overlap areas between the groove orders and the objective lens as the spot moves off track.

A second method used to generate a TES is shown in Fig. 17, which is called *three-spot tracking*.[31] In addition to a central laser spot, two additional laser spots are generated by the illumination optics. These three spots are imaged onto separate detectors A, B and C by the servo optics. The leading spot is imaged onto detector A, and the trailing spot is imaged onto detector B. The central spot, which is used to detect the data signal, is imaged onto detector C. The brightness of the spots at the detectors is determined by the amount of overlap between the spot and the data marks. When the spot is centered over a data mark, its corresponding light level at the detectors is reduced the most. When the data spot is centered over a track, the leading and trailing spots are slightly offset from the center in opposite directions and by an equal amount. Their brightness at the detectors is equal, and the difference between detector signals A and B is zero. When the spots are slightly off track, as shown in Fig. 17, the leading spot is now overlapping less of the data mark and the trailing spot is overlapping more of the data mark. Therefore, the brightness on detector A increases, and the brightness on detector B decreases. The difference between detector currents A and B is now positive. When the spot on the disk shifts in the opposite direction, the difference current becomes negative. The TES is generated from the difference between the currents from detectors A and B, and provides a good quality feedback signal that is directly proportional to the position error in the center of the track. Like with push-pull tracking, the TES for three-spot tracking is periodic with a period equal to the track pitch. Unlike the push-pull technique, three-spot tracking requires that the spots be re-imaged onto the detectors. Three-spot tracking is often used in music CD players, where there is not a land and groove pattern and the TES must be generated from only the data marks.

The popular *astigmatic focus* method to generate a focus error signal (FES) is shown in Fig. 18.[32] The reflected light is directed into the servo lens, which affects light on the detectors in a special way. That is, the light spot on the detector plane changes shape as a function of the disk defocus. When the disk is too close to the objective lens, the light spot elongates along the right diagonal on detector quadrants A and C. When the disk is in focus, the light spot is circular. When the disk is too far from the objective lens, the light spot elongates along the left diagonal on detector quadrants B and D. The FES signal is created by summing diagonal quadrants and then subtracting the results. If the disk is too close to the objective lens, the FES is positive. When the disk is in focus, the FES is zero. If the disk is too far from the objective lens, the FES is negative. Near the focus condition, the FES is nearly linear and provides a good quality feedback signal for the servo loop. The elongated spot behavior is due to a small amount of astigmatism in the fabrication of the servo lens. Astigmatism is a difference in the focusing power in diagonal directions, and is similar to astigmatism that commonly occurs in the eye.

5.7 Noise and jitter

As shown in Fig. 11, the resolution limit of the optical system is determined by the zero of the modulation transfer function. In practice, it is not possible to obtain this limit due to noise. Noise limits the ability of the detection electronics to determine the proper bit pattern from the detector signal.[xref:] Sources of noise include reflectivity variations across the disk, photon noise in the laser beam, detector noise and other sources.[33, 34]

A detector signal with noise is displayed in Fig. 19 for a large spot and a small spot. The same amount of random noise is assumed for both signals. In order to detect the bit pattern, a threshold level is established based on the signal amplitudes. When the signal level falls below the threshold, a *transition* has occurred. The *data bit* value changes from 1 to 0 at the transition marked in Fig 19, where there is one data bit for each mark and one data bit for each space between marks. This minimum mark length is a function of the spot size s, and is generally found to be $0.6s$. Marks and spaces can be longer than the minimum mark length, but they cannot be shorter.

In very simple recording schemes, the data bit may represent the desired output data stream. In practice, the transition signals the change of a *channel bit* value, where more than one channel bit is present for each data bit.[35, 36] It is the channel bits that determine the output data stream and the data density. Each channel bit is defined by a *channel bit window*. Size of the window is determined by how small the window can be before noise degrades the reliability of detecting the transition.

A magnified portion of the transition region is shown in Fig. 20. The amplitude noise σ_N on the signal creates uncertainty σ_w in the position of the transition. A detection error occurs if the noise shifts the transition from the ideal window into a neighboring window. The widow size is usually specified so that uncertainty σ_w produces no more than one error per 10^4 transitions. Variation of the transition within the timing window is called *jitter*. As shown in Fig. 20, the amount of width variation (or jitter) is a function of signal slope. That is, $\sigma_w = m/\sigma_N$, where m is the signal slope.[37] Small spots yield high slope, small σ_w and short channel bit windows.

5.8 Data coding and formatting

The different ways of organizing ones and zeros on the disk are called *formats*.[38] There are several different formats in use today, as illustrated in Tables III and IV, with new ones being invented all the time. Some are more popular than others; some require special drives to access them, while others are compatible with each other to some degree. This section describes the CD-DA (digital audio) format. Details of other formats for CDs are available through the standards set by the industry in a "rainbow" of reference books.[39] That is, a particular book "color" corresponds to a particular standard. For example, CD-ROM format follows the "Yellow Book", CD-DA follows the "Red Book", and CD-R and CD-RW follow the "Orange Book". These standards are important, because they insure interchangeability between different players.[2]

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[2] Similar standards are available for the DVD family of products in specification books labeled as "A" (DVD-ROM) through "E" (DVD-RAM). The DVD coding and formatting philosophy is distinctly different than CDs, in that DVDs are designed from the outset to be more compatible with computers, and a subset of the Universal Disk Format (UDF) is implemented for the file system in both writeable and read-only versions.

The set of rules used to convert user data bits into their physical data-mark representation and back again are called *channel codes*. The channel code for CD-ROM is called eight-to-fourteen modulation (EFM).[35, 36] EFM interprets user's data along with error correction data, address data, synchronization data, and other content into the stream of channel bits recorded in the data-mark pattern. An example of an EFM sequence is shown in Fig. 21, where there are a minimum of two zeros following each transition and a maximum of ten zeros following each transition. The minimum number of zeros is set by the jitter requirement, as explained in Section 5.9, and the maximum length is set by the need to provide a synchronization signal for the reference clock shown in Fig. 19. The conversion of an eight-bit user byte under these restrictions leads to a fourteen-bit channel sequence, from which this code scheme derives its name. A fourteen-bit channel sequence is called a *symbol*. During readout, the EFM decoder of the CD-ROM works in the opposite direction, as shown in Fig. 4, converting the current signal into a binary data stream, which is then cleared of any miscellaneous data by the drive's electronics.

A problem can exist if two symbols follow each other. If a ‘1’ ending the first symbol is adjacent to a ‘1’ of the second symbol, the ‘minimum of two zeros’ separation rule is violated. To solve this problem, three special merge channel bits are placed between the two symbols. Thus, for each eight-bit user byte, seventeen channel bits are used. The seventeen-bit sequence is also called a symbol.

A basic unit of information stored on a CD is called an *EFM channel frame*, which contains a twenty-seven-bit synchronization pattern and thirty-three seventeen-channel-bit symbols. The sequence of symbols by themselves is called an *EFM frame*, which consists of twenty four user data symbols, a control and display symbol, and eight error correction (ECC) symbols, as shown in Table V.[5] The EFM channel frame is the smallest recognizable physical sequence of data marks along a track. In digital audio CDs, sequential music data are scrambled and cross interleaved throughout multiple frames, in a manner similar to digital audio tape (DAT) formats.[40] This scrambling and cross interleaving is done to protect against contamination on the disk or readout errors creating perceptible loss of audio data. During readout, the decoder shown in Fig. 4 first determines the sequential symbols from the disk, then decodes and unscrambles them to produce the output data stream.

In the CD-ROM (Mode 1) format, data are logically organized in *sectors*, which contain 2048 bytes of user data, a twelve-byte synchronization pattern, four bytes of sector identification, and eight additional bytes that are used for other formats, like CD-I. A representation of a CD-ROM (Mode 1) sector is shown in Table VI. Since sectors are simply a logical organization of data, individual bytes in the sector can be distributed across the surface of the CD according to the cross-interleaving scheme. A CD-ROM (Mode 1) sector spans 98 frames over the surface. This sector organization is quite different from physical sectors on magnetic disk drives, where a logical sector corresponds to a continuous length of track.[41] Other CD formats vary in the way the sector is defined and use of symbols within the sector, but the basic EFM channel frame and cross-interleaving strategy is common on all formats.

5.9 Configurations for optical media

Optical media can be produced in several different configurations. Figure 22 displays four configurations that are in commercial use or have been tested in laboratories. The most common configuration is the single-layer disk, like the compact disc (CD), where data are recorded in a single storage layer

In order to increase data capacity of the disk, several layers can be used. Each layer is partially transmitting, which allows a portion of the light to penetrate throughout the thickness of the layers. The scan spot is adjusted by refocusing the illumination optics so that only one layer is read out at a time. Some of the DVD formats in Table IV use two layers on one side of the disk.

Data can also be recorded in volumetric configurations.[42, 43] Like with the multiple-layer disk, the scan spot can be refocused throughout the volume of material to access information. Volumetric configurations offer the highest efficiency for data capacity, but they are not easily paired with simple illumination optics.

The final configuration is to place the information on a flexible surface, like ribbon or tape.[44, 45] Like magnetic tape, the ribbon is pulled under the scan spot and data are recorded or retrieved. Flexible media has about the same capacity efficiency as volumetric storage. The advantage of a flexible medium over a volumetric medium is that no refocusing is necessary. The disadvantage is that a moderately complicated mechanical system must be used to move the ribbon.

5.10 Laser sources

The semiconductor laser diode [xref:?] is a key technology element in establishing the optical data storage industry. Although both the communications industry and the optical data storage industry use laser diodes, the latter consumes orders of magnitude more diodes that the former. Each CD player on the market uses an AlGaAs laser diode that operates with a wavelength around 0.780 micrometers. These small light sources are important, because they can emit a relatively bright beam, they are reliable and they can be directly modulated with simple electronics.

The operating power depends on whether data are being written to the disk or data are being detected during readout. Since optical storage media are thermally sensitive, a relatively high power is required for writing data. For example, CD-R and CD-RW media typically require 5mW to 10 mW at the disk surface during writing. Since there are losses in the optical system associated with shaping the laser diode beam and directing the beam with beam splitters, the typical efficiency of the optical path is around 50%.[46] Therefore, laser diodes that operate with powers greater than 20 mW are generally required. For systems that write data faster than standard playing time, more power is required because the disk spins faster. During readout, the required laser power is greatly diminished. Typical read-only systems require only 0.5 mW.

The mode structure if the laser diode is important for two reasons. First, the source must exhibit good spatial coherence in the transverse mode structure, because most tracking servo techniques depend on an interference effect between diffracted orders, as explained in Section 5.6. Single transverse mode behavior is commonly achieved in commercial diodes over a wide range of operating conditions.[xref:?] The longitudinal mode structure is important also. Laser diodes for data storage applications typically exhibit more than one longitudinal mode.[xref:?] This mode behavior is, in part, due to the inexpensive nature of the device. When the optical system reads data, some amount of light reflected from the disk leaks back to the diode. Feedback effects from this light returning to the laser can influence laser output and increase laser noise, which is a source of jitter. Since jitter must be minimized in order to achieve high density, as explained in Section 5.7, laser diodes are typically modulated at a high frequency (around several hundred MHz) in order to mix the longitudinal mode structure and prevent mode hopping noise due to feedback. This high-frequency modulation produces a low temporal coherence, due to the relative large number of modes observed over the bandwidth of the data detection electronics.

Since the resolution limit is improved by using short-wavelength lasers, modern DVD systems use strained multiple quantum well diodes produced in AlGaInP/GaInP by MOCVD.[47] These diodes typically emit with a wavelength from 0.635 micrometers to 0.680 micrometers. Power levels from the diodes reach 35 mW to 50 mW. Next-generation optical disks will use InGaN violet laser diodes with operating wavelengths around 405 nm.[48, 49]

6.0 Performance

Three important performance characteristics of optical data storage devices are the capacity, data rate and access time.

Capacity	is the maximum amount of data that can be stored on a single disk. Capacity is usually specified in terms of giga-bytes (GB), or 10^9 bytes. (One byte = eight bits).
Data rate	is the number of digital bits per second that are recorded or retrieved from a device during transfer of a large data block. Data rate is usually specified in terms of megabits-per-second (Mbps), or 10^6 bits per second.
Access time	is the latency experienced between when a request is made to access data and when the data starts flowing through the communication channel. Access time is usually specified in terms of milliseconds, or 10^{-3} seconds.

Together, data rate and access time determine the *throughput* of the device. That is, throughput determines the time required to locate and transmit data to and from the storage device.

The data rate can be different for writing and reading data on a disk. During writing, the data rate is determined by the highest medium velocity that produces clearly defined marks. During reading, the data rate is determined by the highest medium velocity that produces sufficient signal-to-noise ratio. One straightforward way to increase data rate is to use more than one laser beam at a time. The increase in data rate is nearly proportional to the number of beams. A consumer CD product based on using multiple beams for readout that are generated with a diffraction grating has been shown to dramatically improve data rate without large increases in disk rotation rate.[50]

The access time is determined by the mechanical latency due to the disk rotation. The highest latency is the time it takes the disk to make one revolution. Reduction of latency requires spinning the disk faster.

Important considerations for storage are the performance requirements of new and existing applications. An illustrative example is found in the CD/DVD marketplace. As introduced in 1991, the CD-ROM exhibited a capacity of 0.64GB and a data rate of 1.2 Mbps. Although today's CD-ROM has the same capacity, market forces have driven the data rate to over 50 Mbps. The increased data rate of CD-ROM drives may have, in part, been responsible for the delayed market acceptance of DVD-ROM. Introductory DVD products exhibit a data rate of 10 Mbps. Thus, computer applications eagerly accept higher speed devices.

A serious limitation exists with disk-based optical data storage. As the data rate increases, the playing time for a fixed capacity decreases. Applications that require long playing times (and correspondingly high capacities) must use multiple disks. For example, a CD-ROM drive operating at 50 Mbps takes only 102 seconds to read the entire disk. Correspondingly, a hypothetical DVD-ROM drive operating at 400 Mbps (a similar speed multiplier compared to the fast CD drive) takes less than 100 seconds to read a 4.7 GB disk.

A useful figure of merit is the *capacity-rate product* (CRP), which is the product of the capacity in GB and the data rate in Mbps. The CRP and other performance characteristics of disk-based products are given in Table VII. The data-rate speedup factor is shown as "1X" or "40X", where 1X refers to the data rate of products first introduced into the marketplace, like the CD-ROM in 1991. 40X refers to a data rate that is forty times faster that the 1X rate. Also included in Table VI are preliminary data concerning the *digital video recorder* (DVR) or Blu-ray, which is under development.[51]

7.0 Future systems

Future illumination optical systems will use high NA and shorter λ in order to obtain smaller spot size and higher data density. The effects of using higher NA and shorter λ are shown in Fig. 23. For example, if the NA of a DVD system is increased to NA = 0.85, the spot size is reduced by 30%. However, the allowable defocus is reduced by 50%. Alternatively, a blue laser operating at λ = 0.405 micrometers and NA = 0.60 achieves nearly a 40% reduction in best-focus spot size at a penalty of reducing the allowable defocus by the same 40% factor. In general, it is desirable to decrease wavelength rather than increase NA due to the difficulty of decreased depth of focus.

Parameters of three generations of optical disk products are shown in Table VII. These systems are evolutionary products. Shortening laser wavelength and increasing NA reduce spot size and increase capacity. The Blu-ray system, which operates at λ = 0.405 micrometers and NA = 0.85, provides a capacity of 27 GB per layer. However, the Blu-ray system is near the limit for conventional optical systems with standard optical materials. For example, increasing NA beyond 0.85 is possible with a conventional optical system, but the engineering challenges are substantial. In addition, most plastic substrates exhibit poor transmission below 0.400 micrometers. Even if a new laser diode becomes available with a wavelength shorter than 0.400

micrometers, it is not clear whether substrate, detector and media technologies can support it. Instead, recent research points to two promising technologies that may provide the fourth generation optical disk.

The first technology is called near-field optics.[52, 53] Near-field optics use a transducer, like a small hole in a metal film or a special lens element, to produce a light spot that is smaller than the ideal spot size given by $s = \lambda/\mathrm{NA}$. However, the tradeoff for smaller spot size is that the recording layers now must be in proximity to the transducer. The evanescent energy in the spot that couples from the transducer to the recording layers falls off exponentially with distance.

Invented by Prof. Gordon Kino and colleagues at Stanford University, the solid immersion lens (SIL) is under investigation as a possible candidate near-field transducer.[54] The basic SIL system is shown in Fig. 24, where the optical system is supplemented with a hemispherical lens element. When the focused light from the objective lens enters the SIL, the velocity of the light slows down according to n, the index of refraction of the lens.[xref:] Marginal ray angle θ is not deviated by the hemisphere as it enters the lens material, so $\theta' = \theta$. Since the laser frequency does not change, the effective wavelength of the light reduces and the spot size is now given by $s = \lambda/(n \sin \theta') = \lambda/\mathrm{NA}_{\mathrm{eff}}$, where $\mathrm{NA}_{\mathrm{eff}}$ is the *effective numerical aperture*. In laboratory systems, $\mathrm{NA}_{\mathrm{eff}}$ approaching 2.0 have been demonstrated.[55] When coupled with a blue laser diode, the potential of a SIL system is to increase capacity beyond a factor of four above the Blu-ray system. However, control of the gap that separates the SIL from the recording layers is a difficult engineering problem, especially if the optical disk is removable from the optical drive.

A second possible technology for fourth-generation optical disks is called magnetically amplifying magneto-optical system (MAMMOS), which is similar to MO systems described in Section 4. MAMMOS technology take advantage of the fact that the primary limitation to resolution in optical data storage systems is reading data, as explained in Section 5.3. With a pulsed laser and a modulating external field, magnetic domains can be written in the recording layer that are much smaller than the resolution limit.[56] Readout of these marks in a MAMMOS system is illustrated in Fig. 25, where a multiple-layer MO stack is used. Each MO layer reacts differently to the heat deposited by the laser beam. The bottom layer, which is called the recording layer, contains the written information in the form of small bits. This layer has a high coercivity, and it is not easily affected by the relatively low temperature profiles generated by the readout beam. The top layer is the expansion layer, and it has a low coercivity, among other special properties. The middle layer is a thin nonmagnetic layer. When the readout beam heats the expansion layer, magnetic energy from the recording layer couples into the expansion layer and forms an expanded copy of the recording layer in it. Only a small region of the storage layer around the center of the laser spot is copied. Expansion of the bit pattern produces a magnified image in the expansion layer. To the readout optical system, it appears that the light spot travels over relative large marks, which produce good signal-to-noise ratio. Capacity of MAMMOS systems have been demonstrated to be about three times greater than Blu-ray disks.[57] Potential difficult in MAMMOS systems lies in economically producing disks and player systems.

Other systems are also worthy of mention, because disruptive technologies are always possible. For example, near-field super-resolution structures (SuperRENS) combine a nonlinear optical material layer with a conventional phase-change media structure.[58] This system has the advantage of using near-field optical effects with a conventional readout system. It is not necessary to maintain a small gap, as required in the SIL systems. Also, volumetric storage systems show promise. Instead of recording only on one or two layers, volumetric bit-wise systems store data on several hundred layers through the thickness of the disk.[59] Volumetric bit-wise system may need to use nonlinear properties of the recording layers in order to record data marks without interference from other layers. Finally, optical data storage and magnetic disk storage may converge into *hybrid* recording, which uses the optical beam only as a heat source to lower the coercivity for magnetic writing.[60] Hybrid readout may be accomplished with magnetic sensors, and hybrid recording may use near-field optics.

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Table I. Four technologies of commercial optical disks.

Disk Technology	**Description**
CD-ROM or DVD-ROM	Compact-disc (CD) and digital versatile disc (DVD) products use pit-type technology. CD and DVD products are read-only memories (ROMs), that is, they are used for software or entertainment distribution and cannot be used for recording information.
CD-R	Compact-disk-recordable (CD-R) products use dye-polymer technology. CD-R products can be used for recording information, but, once the information is recorded, it cannot be erased and reused.
CD-RW	Compact-disk-rewriteable (CD-RW) products use phase-change technology. Data can be erased and the disk reused.
MO	Erasable disks using magneto-optic (MO) technology are popular for work-station environments. Data can be erased and the disk reused.

Table II. CD-R materials, reflective layer, and the resulting color as observed through the clear side of the substrate.

	Disk Color	
Dye Material	Gold Reflector	Silver Reflector
Cyanine	Green	Green/Blue
PhthaloCyanine	Gold	-
Metallized Azo	-	(Dark) Blue
Advanced PhthaloCyanine	Gold	-
Formazan (hybrid Cyanine/PhthaloCyanine combination)	Green/Gold	-

Table III. CD formats

Format	Data-Mark Technology	Characteristics
CD-ROM	pit	Computer storage medium with the capacity of up to 700 MB
CD-R	dye polymer	Write-once computer and audio storage > 700 MB
CD-RW	erasable phase change	Erasble > 700 MB storage with > 1000 erase cycles
CD+G (CD+Graphics	pit	Audio CD plus additional graphics and/or text information recorded in R-W subcodes
CD+Midi	pit	Audio CD plus MIDI music information in the R-W subcodes to enable sounds from CD to be re-voiced or remixed through the MIDI compatible device.
CD-3 (3"CD)	pit	Audio CD with the smaller diameter - (3") with playing time reduced to 20 minutes. Also called CD-single
CD-A (CD Audio)	pit	Original, audio compact disc, containing up to 74 minutes (suggested by "Red Book") of stereo digital audio along with 8 subcode tracks labeled P-W
CD-E (Erasable)	erasable phase-change	Audio or data CD which can be recorded and erased many times
CD-EG (CD Extended Graphics)	pit	Enhancement to the CD+G format adding 256 colors and instant mix of two pictures
CD-I (CD-Interactive)	pit	Extension of the CD-ROM format aimed specifically to the consumer market. System offers high resolution graphics, still and (recently) moving pictures and stereo sound. The CD-I player also plays back CD-A, CD+G and Photo CD.
CD-I Ready	pit	A CD-A that contains additional data "Hidden" in a space before the first track. Loaded into a CD-I player the disc offers many features of full CD-I.
CD-ROM XA (Extended Architecture)	pit	Development of the CD-ROM which has been designed to meet the multimedia and interactive needs. Audio, graphics and (some) video information have been added to original CD-ROM format.
CD-V (CD Video)	pit	Also known as the LaserDisc containing up to 2 hours of analogue video and digital audio information. There are three formats 12", 8" and 5".
CD-V Single	pit	A version of the CD-V containing up to 5 minutes of video plus 20 minutes of CD audio only.
CD-WORM (Write Once, Read Many)	dye polymer	Audio CD allowing direct recording (only once) of musical information. Used also for storing of computer data or copying of CD-ROMs.
CDTV	pit	A version of the CD-ROM discs written in the AMIGA language with the interactive and graphics possibilities.
MINI DISC	magneto-optical	A SONY 2" rewritable magnetooptical disc which is using data reduction system to record up to 74 minutes of the audio information (possible use for computer data storage)
Photo CD	dye-polymer	A KODAK development which is using a CD-WORM system to record up to 100 still pictures. The player is compatible with the CD-I system). To be able to read these disks, CD-Player must be "multi session"
Video CD	pit	CD using MPEG-1 encoding process to compress video (including feature films) on CD. The picture quality is higher than in standard CD-ROMs, but additional hardware (MPEG encoder) is necessary.

Table IV . DVD formats

Format	Data-Mark Technology	Characteristics
DVD-5	pit	Single layer 4.7 GB read-only DVD.
DVD-9	pit	Dual layer 7.95 GB read-only DVD. Both layers are read from one side of the disk.
DVD-10	pit	Double sided 8.7 GB DVD. Must turn disk over to read second side.
DVD-18	pit	Dual layer, double sided 17.1 GB read-only DVD. Can read two layers from each side.
DVD Video	pit	One of DVD-5 through DVD-18 with MPEG-1 or MPEG-2 video files, audio, subpictures and navigation data.
DVD Audio	pit	DVD-5 with high-quality audio files.
DVD-ROM	pit	One of DVD-5 through DVD-18 with computer-friendly file formats.
DVD-R	dye-polymer	Write-once 4.7 GB/side
DVD+R	dye-polymer	Similar to DVD-R, except designed to be compatible with DVD+RW
DVD-RAM	erasable phase change	Erasable computer-friendly random access with 4.7 GB/side. Number of erase cycles > 100,000. Not compatible with all players.
DVD-RW	erasable phase-change	Erasable with better compatibility than DVD-RAM and > 1000 erase cycles.
DVD+RW	erasable phase change	Similar to DVD-RW, except designed to be compatible with DVD-ROM and DVD Video players
DVD-VCD	pit	CD-V authored on a DVDR/W. Audio has to be resampled to 48 khz.
DVD-SVCD	pit	SVCD authored on a DVDR/W. Higher quality video than DVD-VCD. Audio has to be resampled to 48 khz like the DVD-VCD.
DVD-MP3	dye polymer	MP3s burned on a DVDR/W.
miniDVD	pit	DVD format on a CD-R(W) instead of a DVD disc. miniDVD is also sometimes called cDVD. A miniDVD only fits about 15 minutes video on a 650 MB CD-R(W) . This fis not a supported format.

Table V. EFM Channel Frame of a Compact Disk (contiguous in along track)

Synch	Control and display	User Data	ECC
27 bits	17 bits (1 symbol)	408 bits (24 symbols)	136 bits (8 symbols)
	←-- 561 bits (33 symbols) = 1 EFM frame--→		
←-- 588 bits = 1 EFM channel frame ---→			

Table VI. CD-ROM Logical Sector After Decoding

Synch	Address	Mode	User Data	ECC	Reserved
12 bytes	3 bytes	1 byte	2048 bytes	280 bytes	8 bytes
←-- 2352 bytes --→					
←-- 98 EFM frames --→					

Table VII. CRP

Parameter	CD-1X	CD-40X	DVD-1X	DVD-40X	Blu-ray 1X
capacity (GB)	0.64	0.64	4.7	4.7	20
data rate (Mbps)	1.2	48	10	400	25
CRP	0.77	30.7	47	4700	500
retrieval time (min)	70	1.7	62.7	1.6	106.7

Table VIII. Parameters of optical disk products

Parameter	**units**	**CD**	**DVD**	**Blu-ray**
Wavelength	micrometer	0.78	0.65	0.405
NA		0.45-0.5	0.6-0.65	0.85
Track Pitch	micrometer	1.6	0.740	0.320
Shortest Pit	micrometer	0.831	0.399	0.138
Density	Gb/in^2	0.4	2.8	15.9
Capacity	GB	0.65	4.7	27

FIGURE CAPTIONS

1.) This picture of lines written by an electron beam was the inspiration for the invention of the videodisk in the late 1950's. Lines in the lower left-hand corner of the picture are 0.030 micrometers wide and spaced by 0.070 micrometers. If it were possible to reliably record data at this density, a 130 mm diameter optical disk would have several thousand times the capacity of a digital versatile disc (DVD).

2.) Small sections of a compact disc (CD) and a digital versatile disc (DVD) are displayed relative to the laser spots that are focused onto them during recording and readout.

3.) The process of recording data onto an optical disk starts with the user input data stream converted to a current drive signal for the laser diode. Intense pulses from the laser cause physical changes in the surface of the recording medium as the disk spins, which result in spiral tracks of data marks.

4.) A constant, low power laser beam scans a data track to readout data from the disk. Reflected light, which is modulated by the data-mark pattern, causes modulation in the reflected light. The reflected light is directed to servo and data detectors with a beam splitter, which convert the light modulation in a current signal that is then decoded.

5.) An optical disk is used so that the focusing laser light is passed through the clear side of the substrate and illuminates the data-mark pattern on the other side. The thickness of the cover layer is designed to reduce effects of contamination on the surface of the disk, like dust or fingerprints.

6.) The process of recording data marks on CD-RW media. In (A), a laser power modulation with three peaks creates a pattern of three amorphous marks in a bright crystalline background. Overwriting of new data are shown in (B), where a different laser pulse pattern is used. The bias power is used to produce the annealing of the medium into the crystalline state, while the peak laser pulses are use to quench the medium into the amorphous state.

7.) Detail of the laser spot irradiance distribution near the focus of the data marks. Energy falls off rapidly with defocus Δz, and the spot has a finite width s. Multiple thin-film layers are used to enhance recording and readout characteristics of CD-RW media.

8.) A) Magneto-optic recording involves heating the recording layer with the focused laser spot in order to reduce the layer coercivity. Domains in this small region can then be flipped with an externally applied magnetic field in order to form the data-mark pattern. Once the bits cool, they are frozen in place until heated again. B) During readout, a low-power focused spot illuminated the data marks. Linearly polarized light from the laser is rotated either clockwise or counterclockwise, depending on domain orientation. The data detector senses the polarization change and converts this information in to a current signal.

9.) Since optical disk media are sensitive to a thermal threshold, simulated thermal contours of a laser spot scanning the recording surface show isotherms that predict the mark size and shape.

10.) The data-mark pattern reflects light in a diffraction pattern consisting of three primary cones, which are the zero and +/- 1st diffraction orders. As the data pattern moves under the laser spot, relative phase of the +/- 1st diffracted orders changes. In the overlap area between orders, the phase difference produces an interference effect that modulates the irradiance level. This light modulation is then converted into a current signal by the detectors. The amount of overlap area, and hence the amplitude of the data signal, depends on the spatial frequency 1/T of the data-mark pattern. Higher-frequency patterns produce smaller overlap area.

11.) The modulation transfer function is a plot of signal contrast versus spatial frequency of the data-mark pattern. Defocus blurs the laser spot and reduces contrast, especially in the mid-frequency range. Equalization circuits can be used to boost the transfer function after the light modulation has been converted into a current signal.

12.) The relative irradiance distribution of a focused DVD-like laser spot is shown with different amounts of defocus. More than 0.5 micrometers of defocus significantly degrades the peak irradiance and spot quality.

13.) A basic diagram of the servo loop used in optical storage devices shows the gain (G) of the drive electronics producing current for the actuator (H), which positions the lens over the data track. A feedback sensor provides an error signal for robust control of spot position.

14.) A photo of a commercial CD actuator assembly that illustrates the objective lens, suspension flexure, and the coils used to move the suspension.

15.) The push-pull tracking error signal (TES) is generated by using a slit-cell servo detector and sensing the difference in light level between the cells. Since grooves of the disk diffract light like a grating, diffracted orders overlap, as describes with Fig. 10. (In this case, spatial frequency of the grating is fixed, and the diffraction occurs in an orthogonal direction compared to diffraction from data marks.) As the laser spot moves off track, the relative phase change in the diffracted orders produces bright and dark patterns on the detector. The TES difference signal indicates the relative off0track location of the laser spot.

16.) Diffracted from the disk contains orders from the data-mark pattern and the grooves.

17.) Three-spot tracking uses two auxiliary laser spots that ride edges of the track as the disk spins. The spots are reimaged onto separate detector elements. If the data track is not centered, the amount of light reflected from each auxiliary spot changes. One detector spot becomes brighter, and the other dims. A difference signal produces a reliable TES.

18.) The astigmatic focusing technique uses a special lens in the servo optics before a quadrant-cell detector. The lens introduces a small amount of astigmatism into the beam along a diagonal direction on the detector. As the spinning disk goes into and out of focus, the astigmatism forces the light spot to change shape. A difference signal from the detector quadrants produces an FES that indicates the amount of defocus.

19.) Detector signals with noise are shown for scanning data marks with two spot sizes. The width of the channel-bit window is determined by the reliability of detecting a transition across a threshold level. Transitions determine the potions of channel-bit 1's in the data pattern, so data marks and spaces represent more than one channel bit.

20.) Small spots produce high slopes in the transition region, and the signal is less affected by noise as compared to the system with the larger spot. Therefore, laser systems the generate smaller spots can pack more channel bits into the data mark sequence.

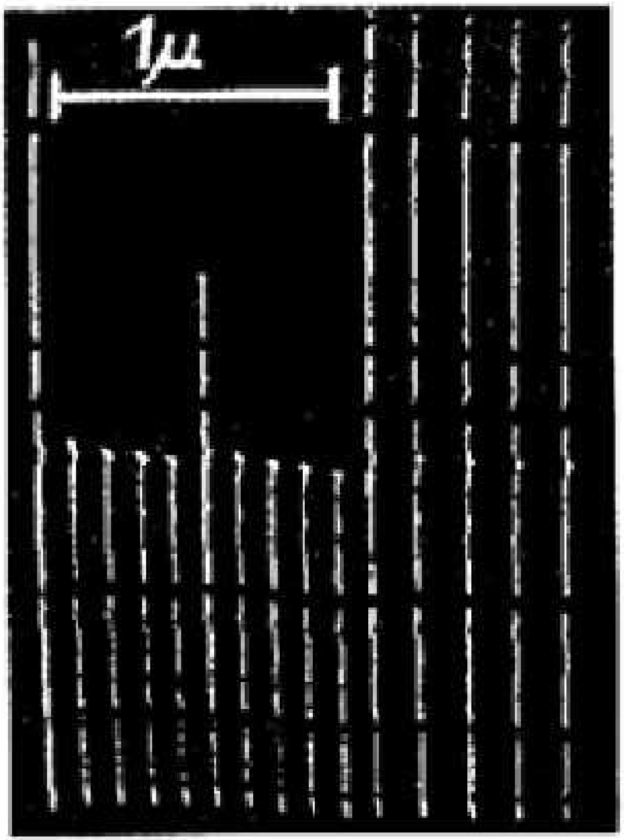
21.) An eight-to-fourteen (EFM) modulation code produces a laser pulse signal and data-mark pattern that exhibits a specific number of zeros between each transition.

22.) Four possible configurations of optical storage media include a single-layer substrate, like a CD, a multiple-layer substrate, like a DVD, volumetric configurations, like holographic and bit-wise storage, and ribbon (tape) media.

23.) Future optical data storage systems will exhibit both higher NA and shorter wavelength lasers. Decreasing wavelength rather than increasing NA has the advantage of a larger depth of focus.

24.) A solid immersion lens (SIL) system uses a image-centric hemisphere in near contact to the recording layers. The SIL increases the effective numerical aperture of the system by a factor of the lens refractive index, and thus decrease the focused spot size by the same amount.

25.) The magnetically amplifying magneto-topical system (MAMMOS) uses a special configuration of magnetic layers to produce good signal readout from a very small data mark pattern.



Milster: Optical Data Storage

Figure 1

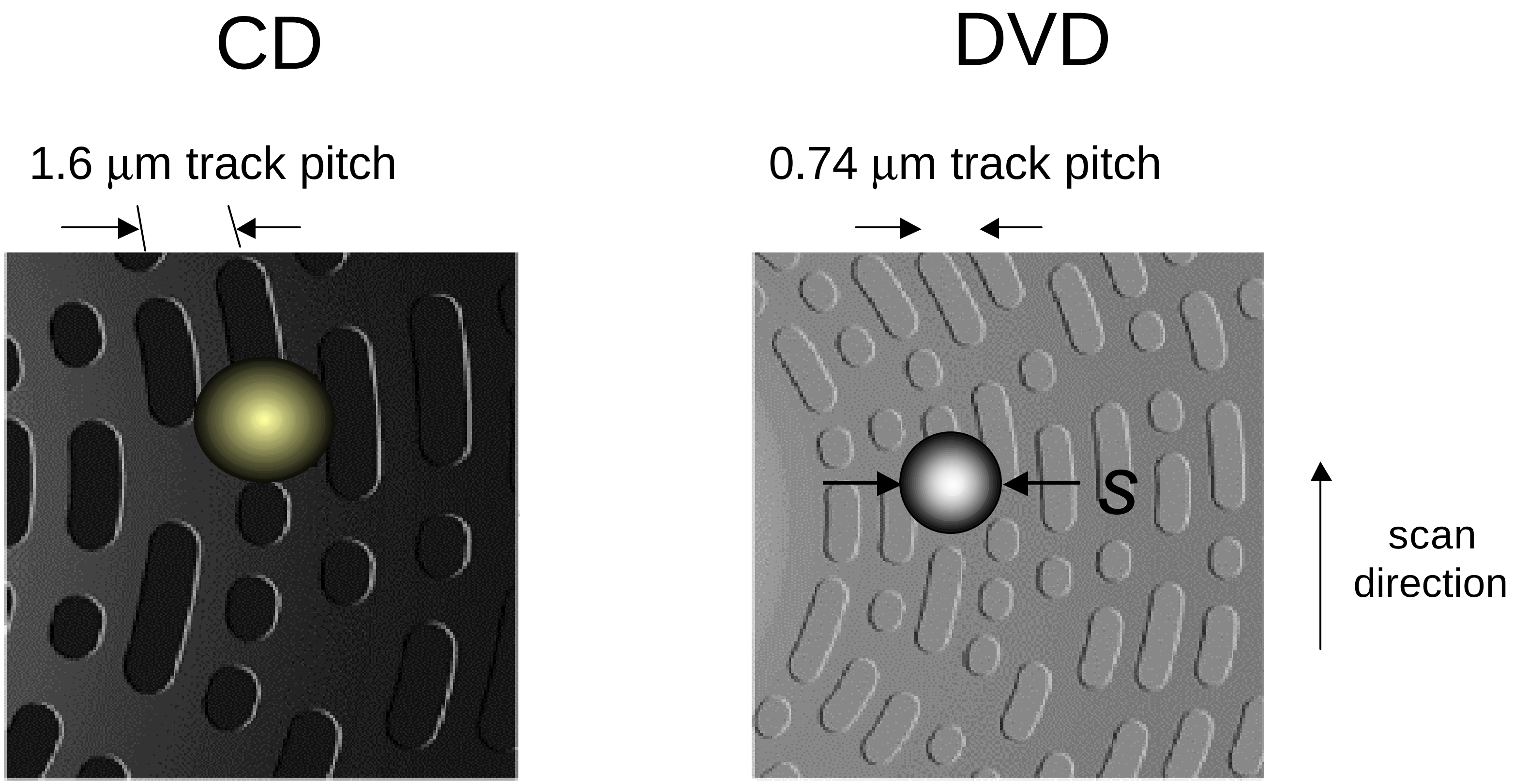


Figure 2

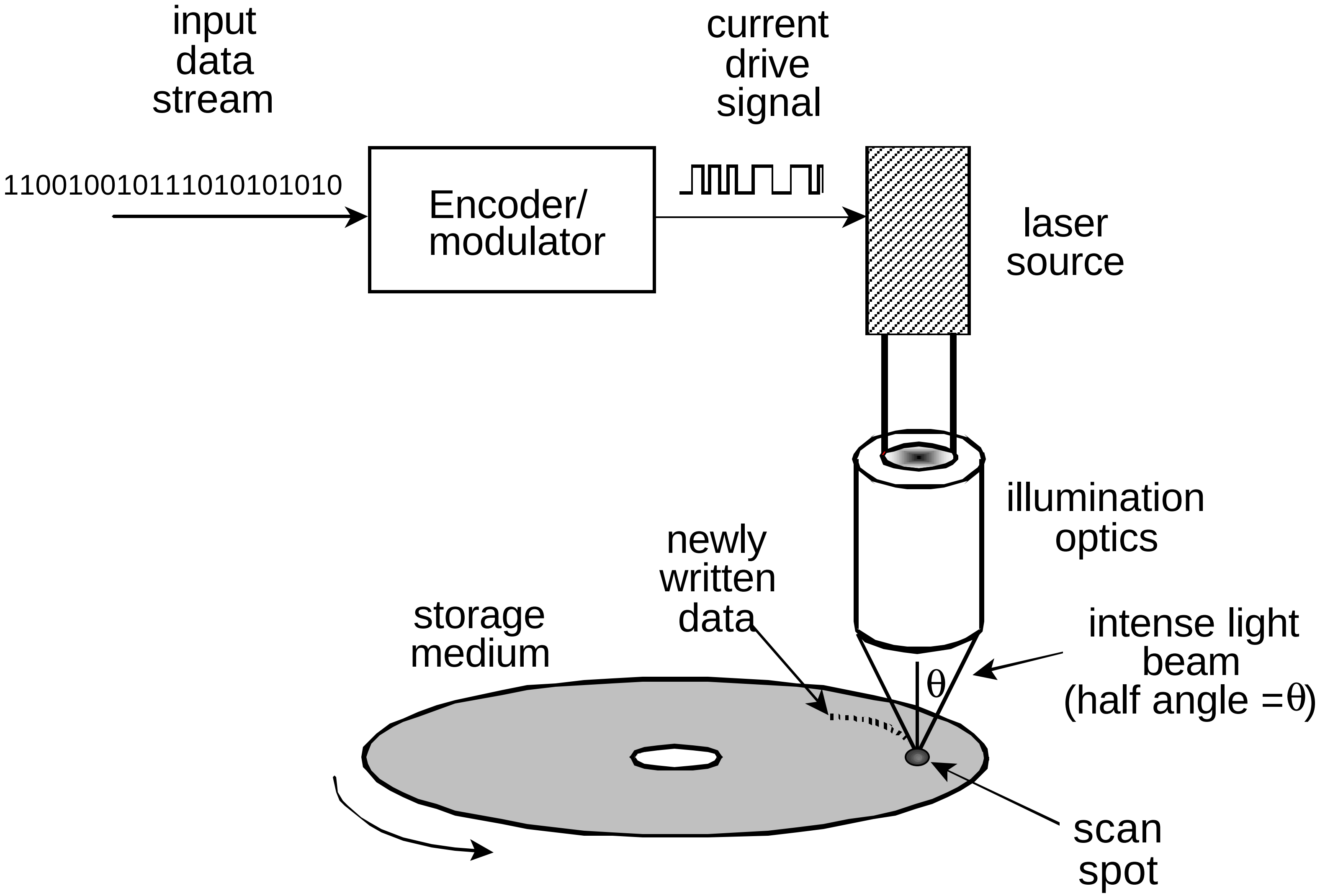


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Figure 3

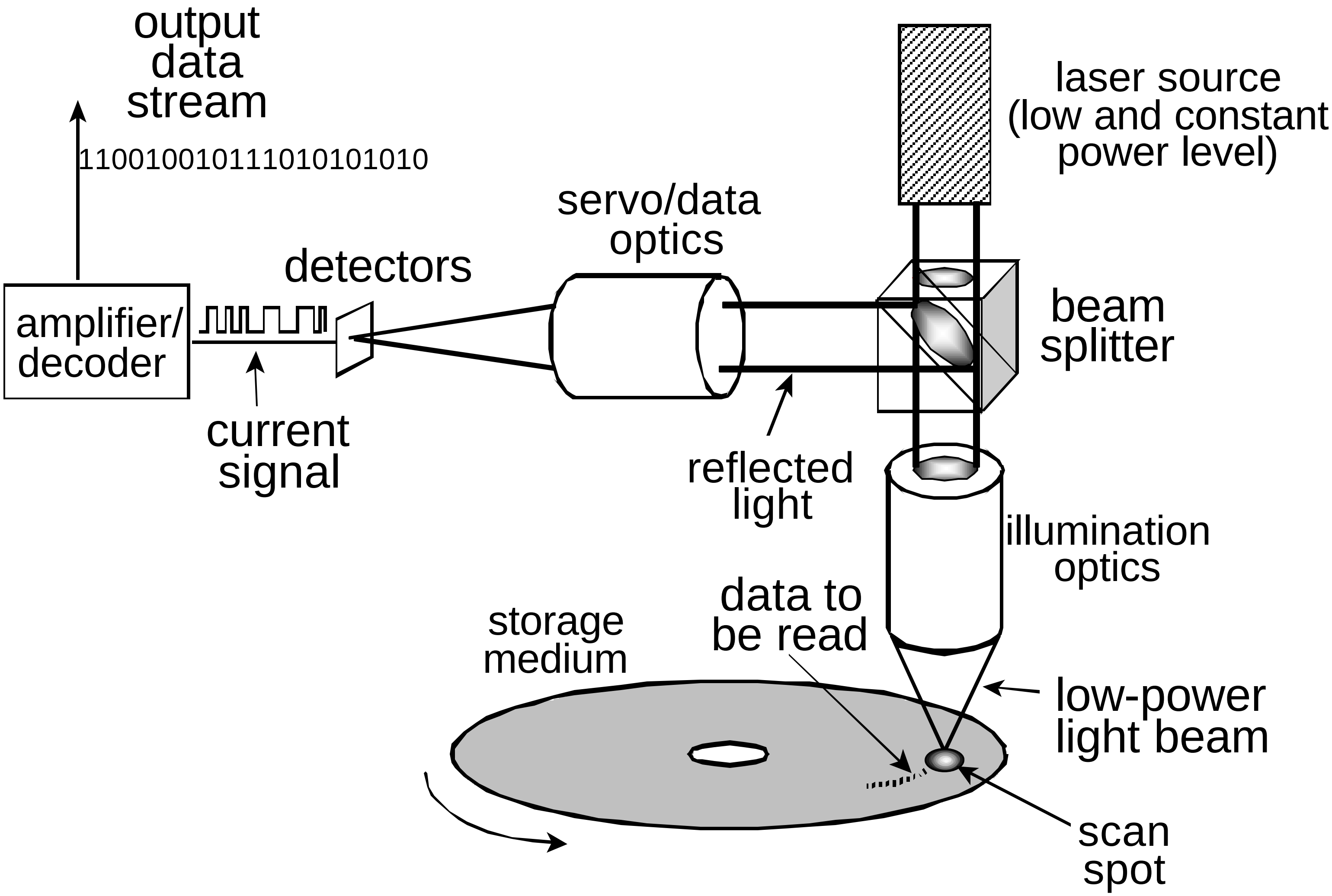

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Figure 4

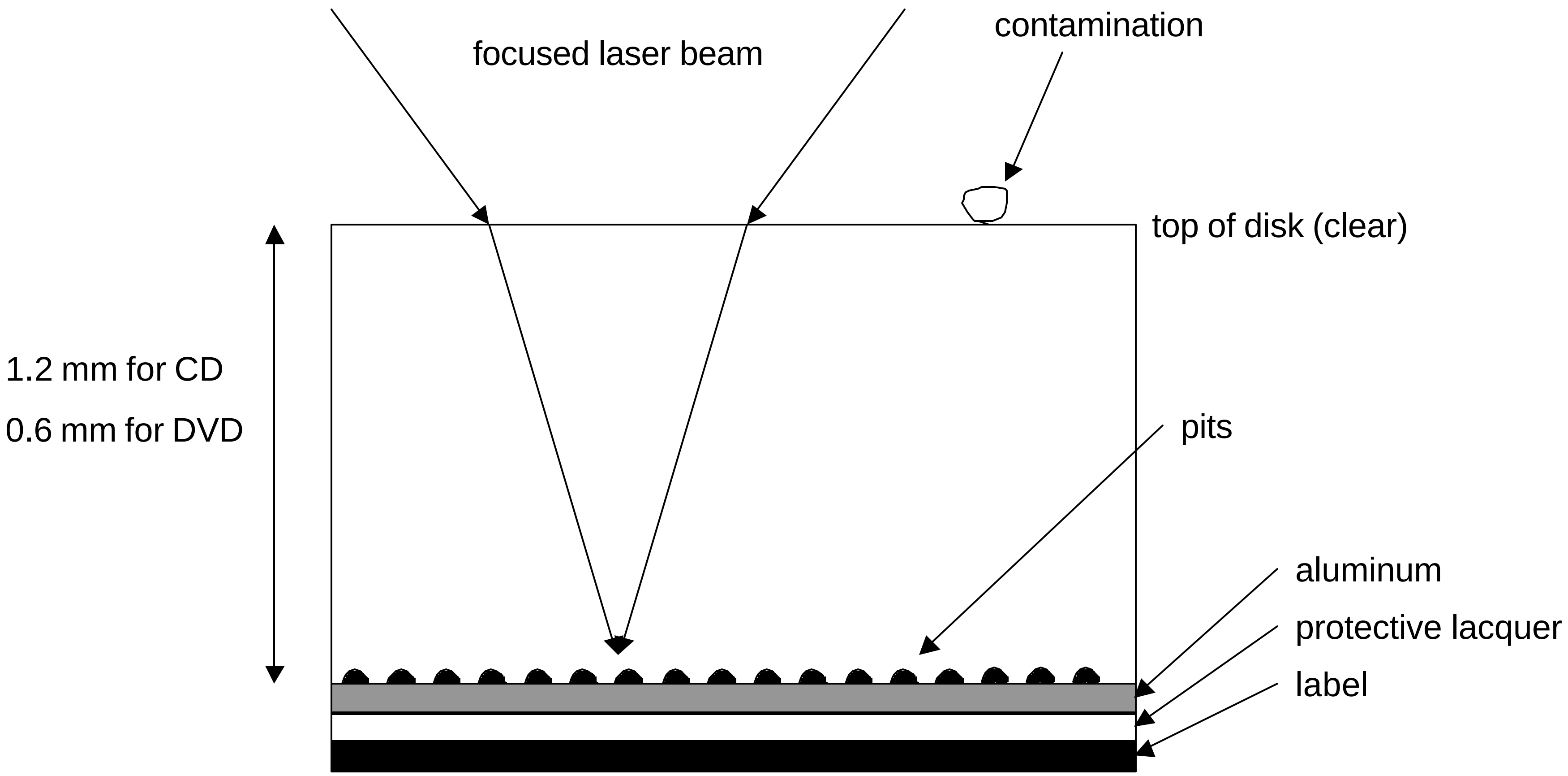

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Figure 5

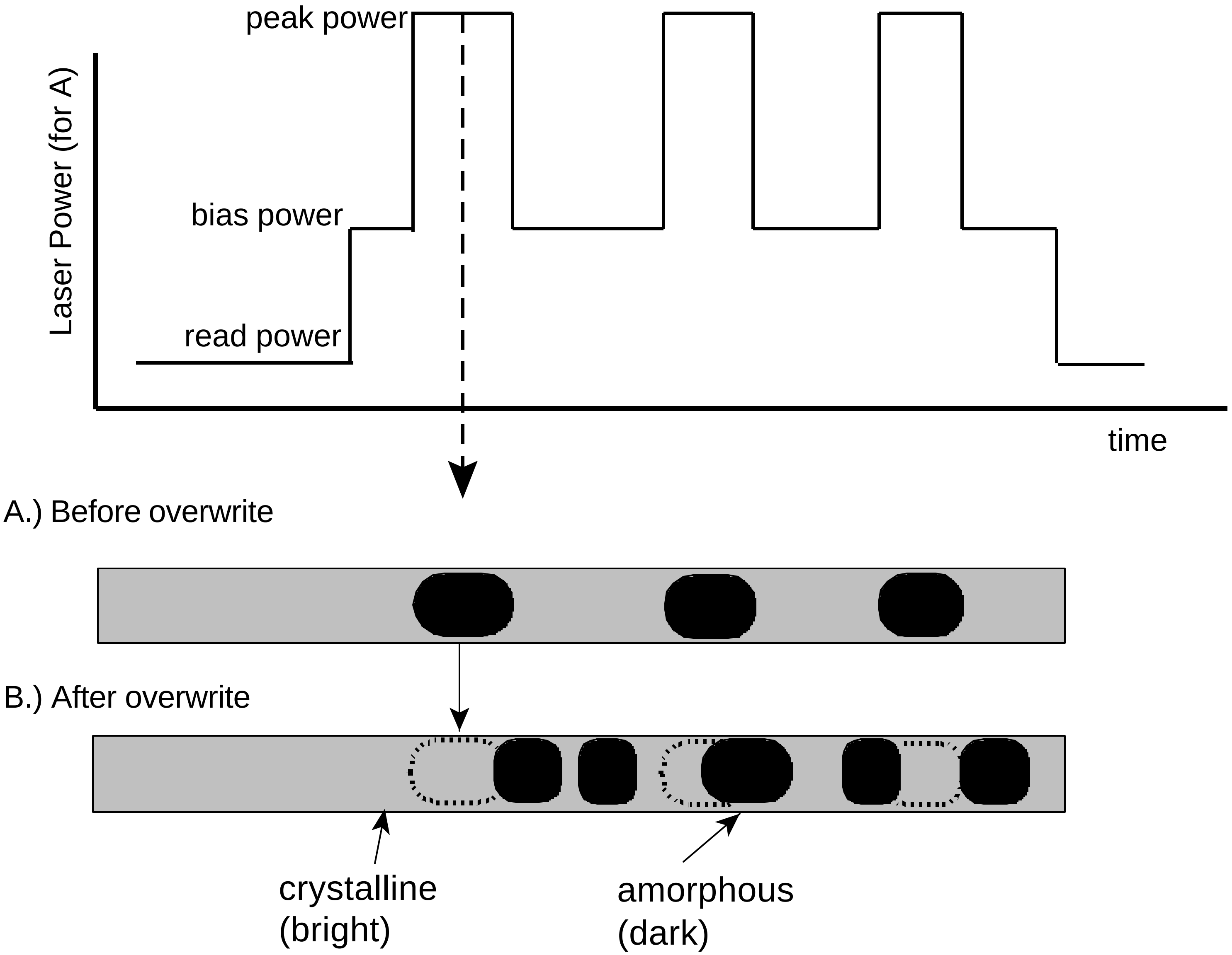

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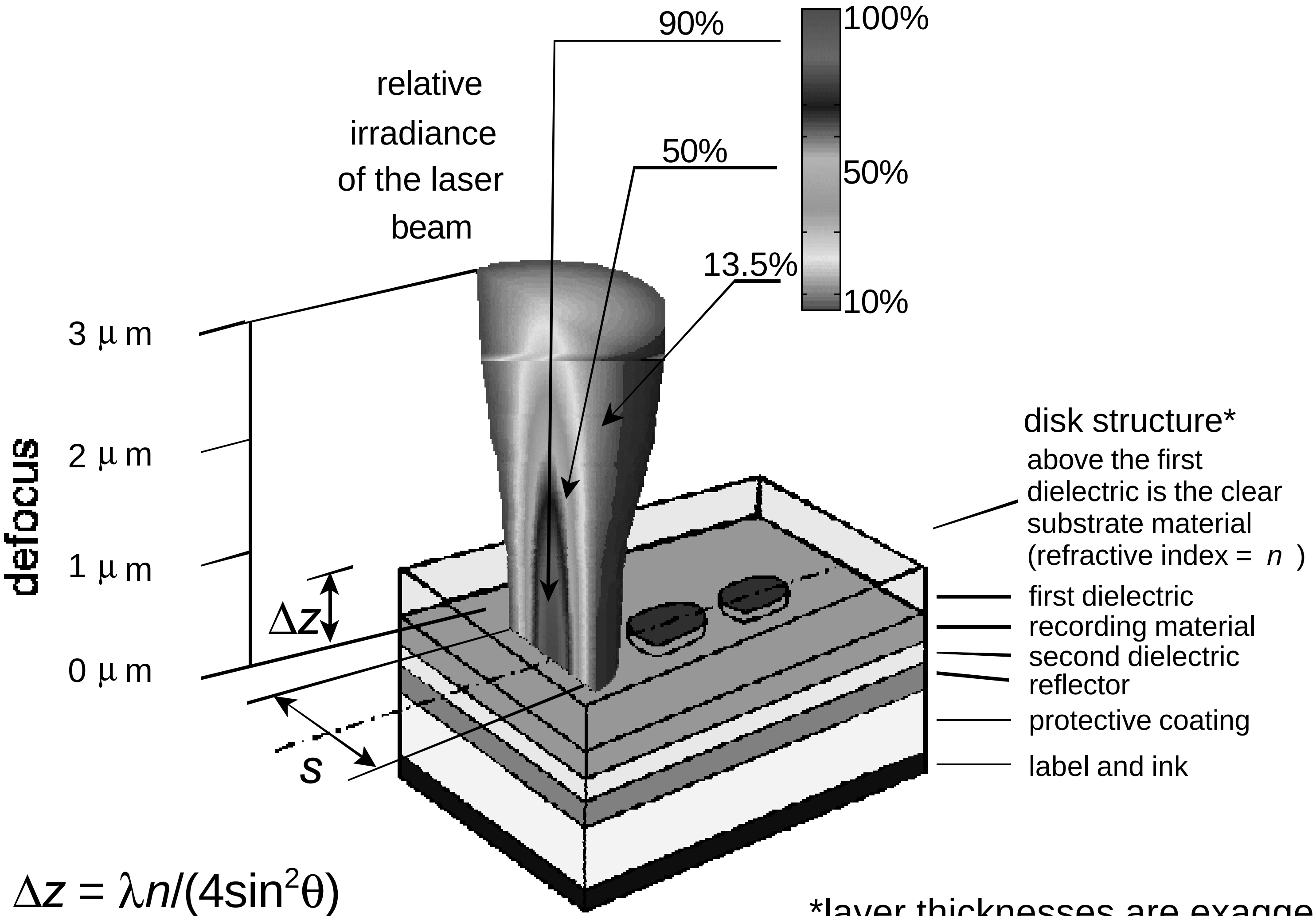
Figure 6



$$\Delta z = \lambda n/(4\sin^2\theta)$$
$$s = \lambda/(n \sin\theta)$$

*layer thicknesses are exaggerated

Figure 7

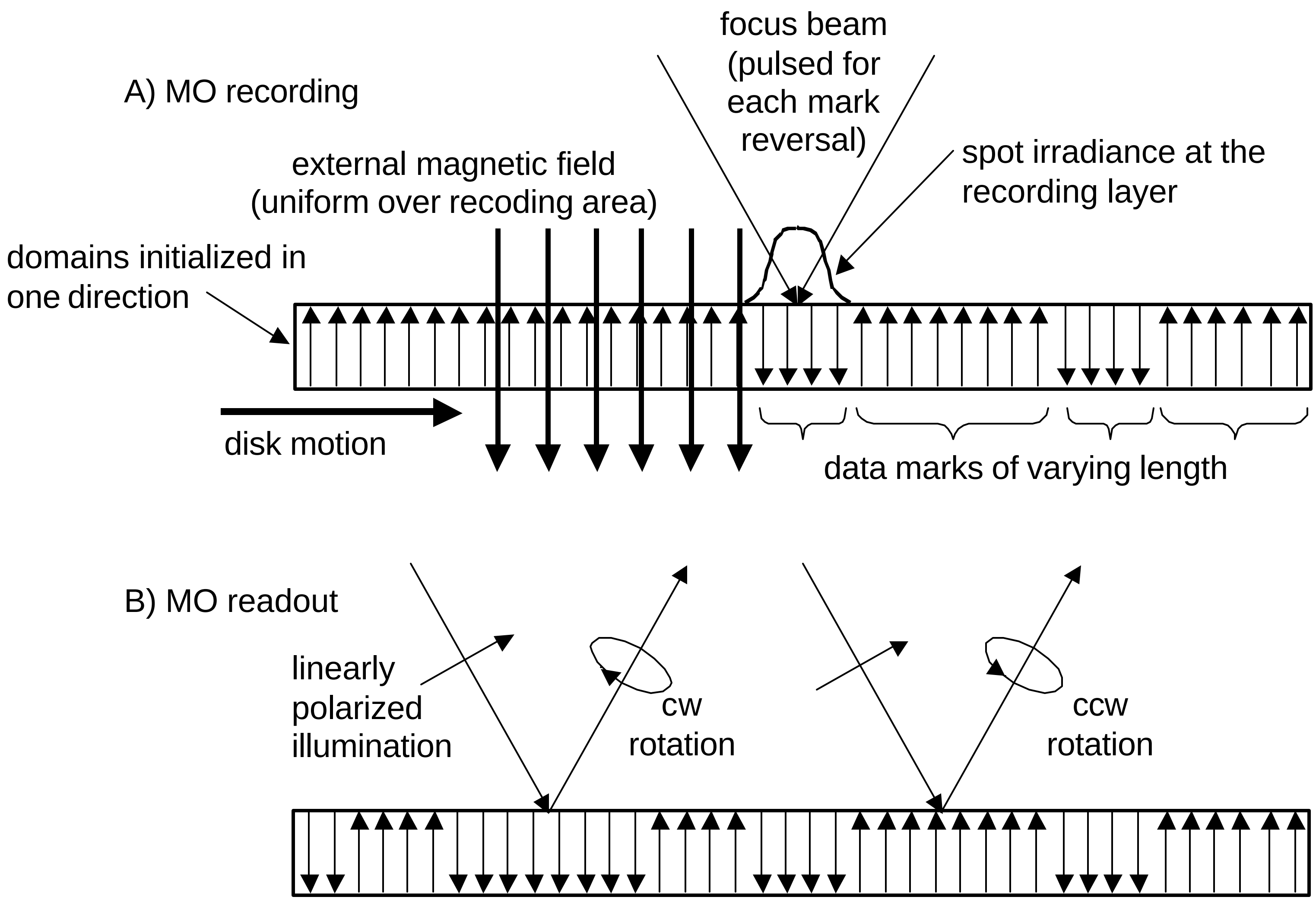


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Figure 8

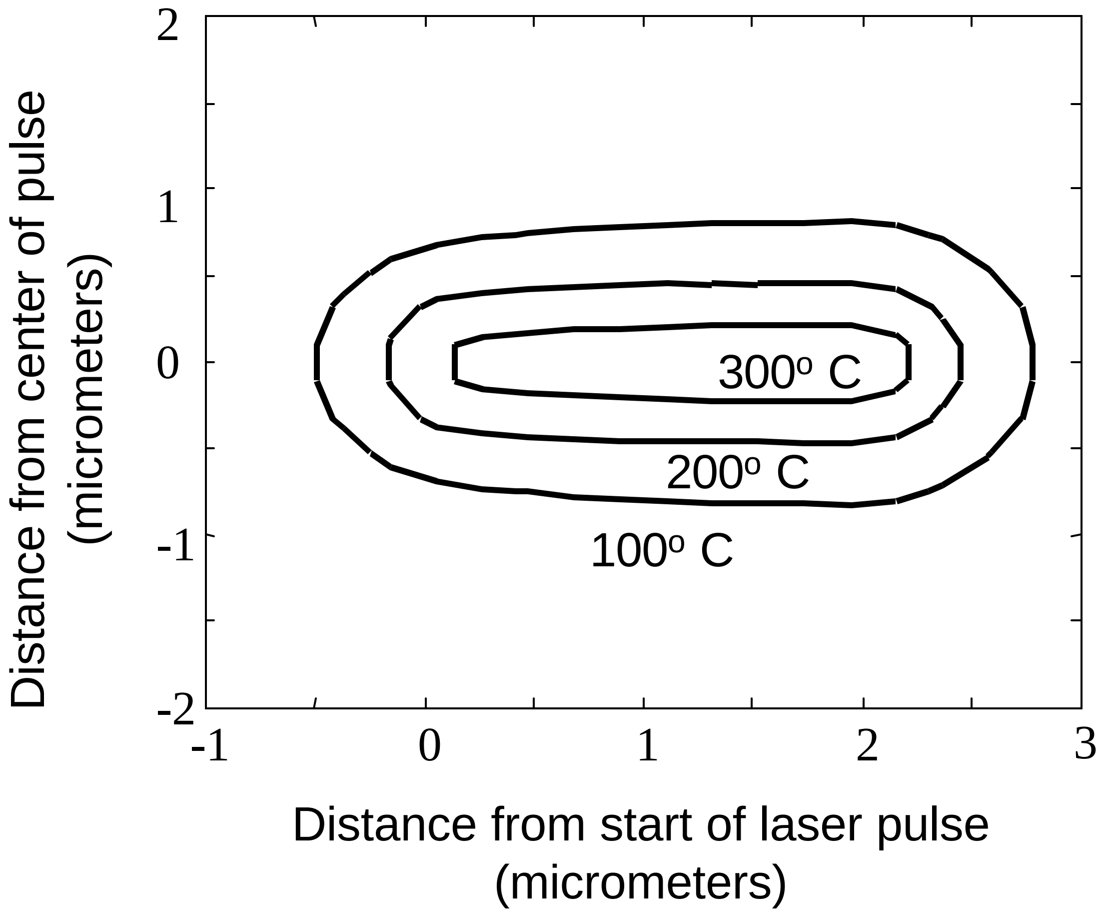
2
1
0
-1
-2
-1
0
1
2
3
300° C
200° C
100° C
Distance from center of pulse (micrometers)
Distance from start of laser pulse (micrometers)

Figure 9

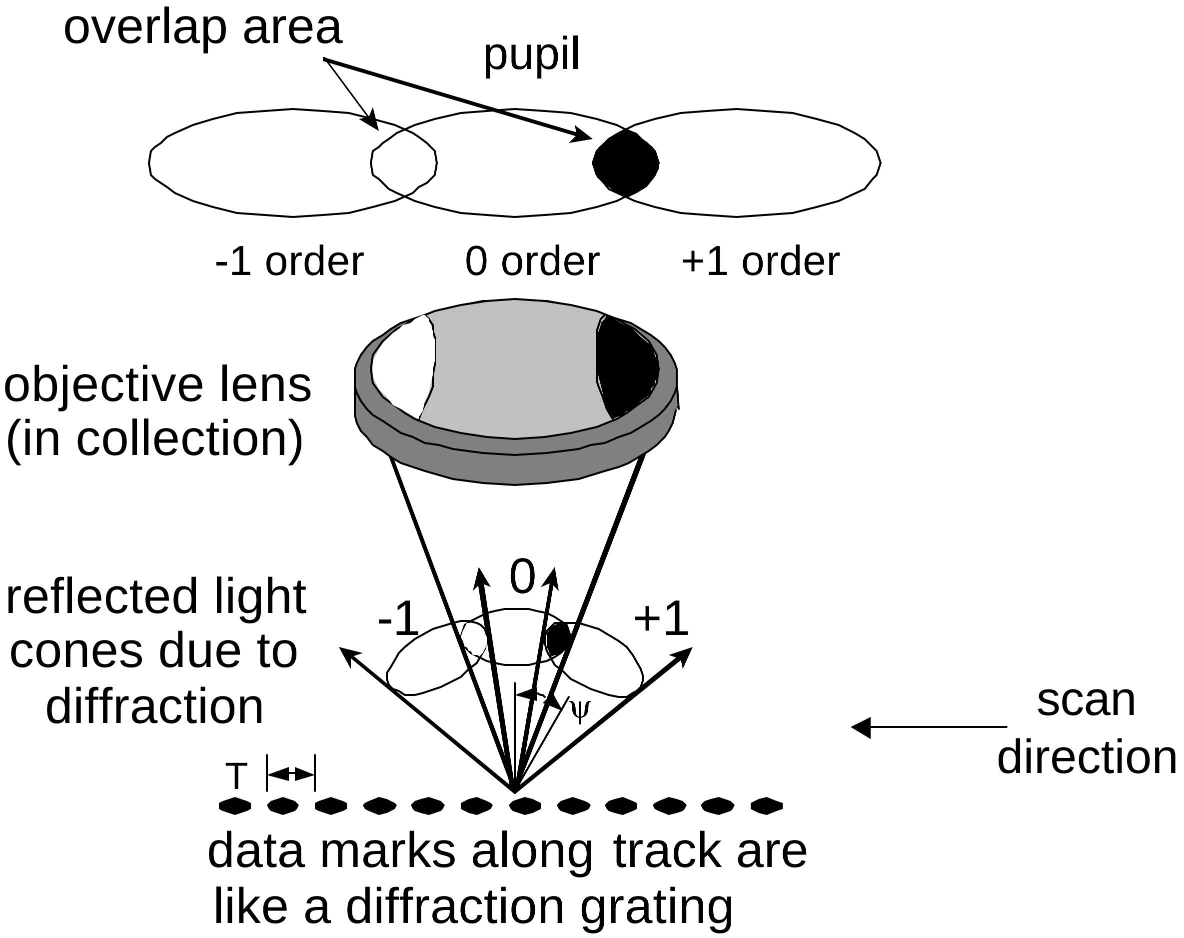

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Figure 10

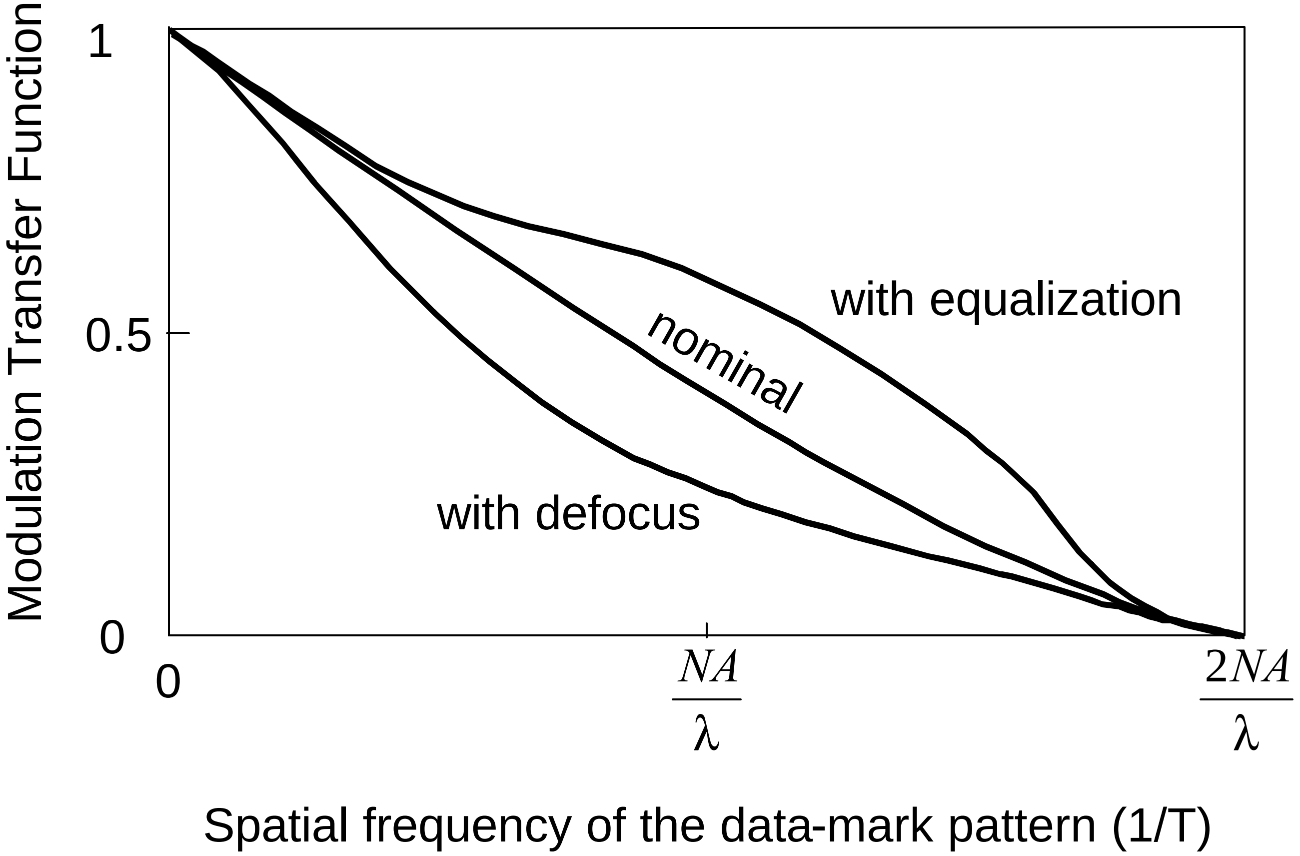

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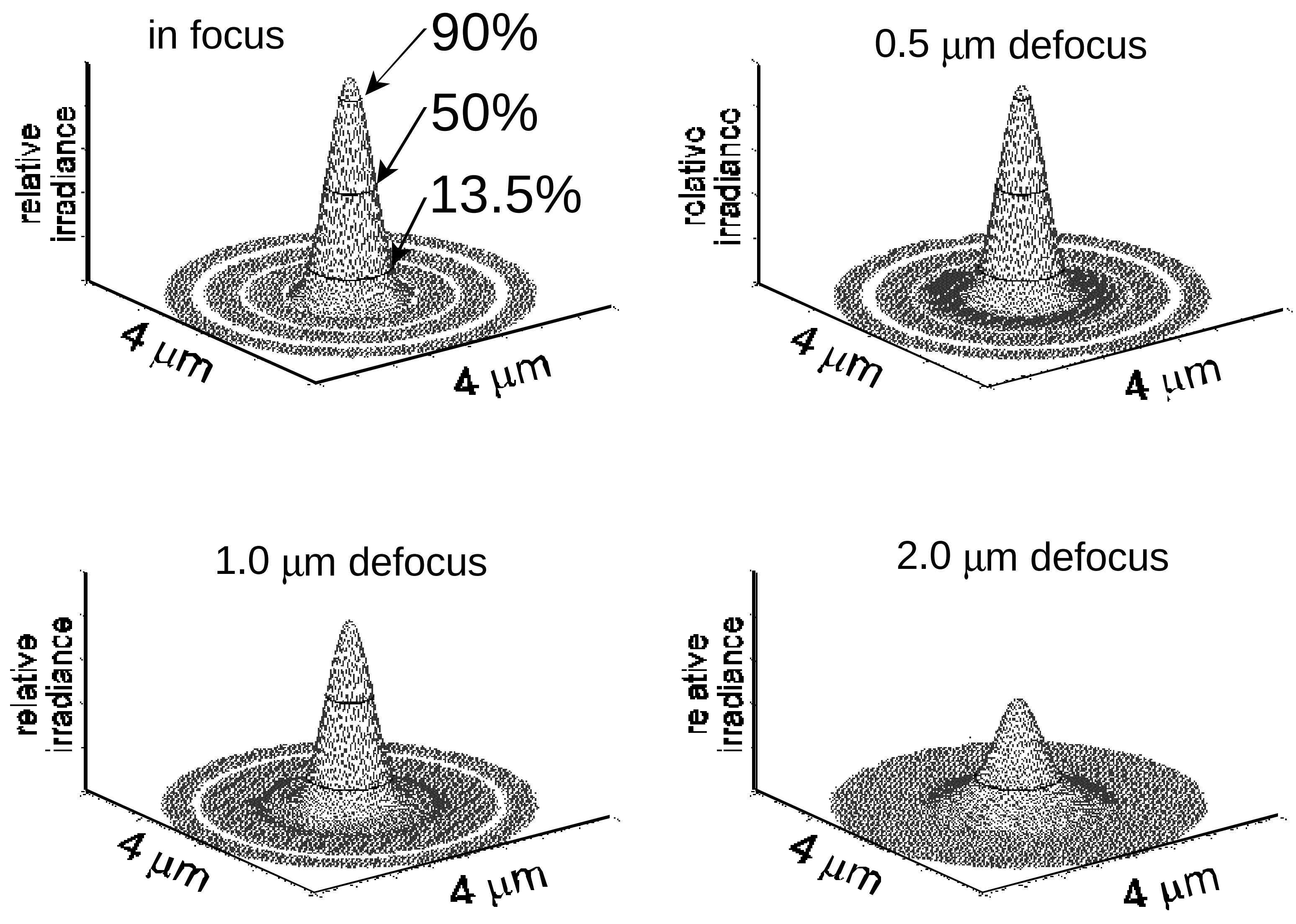
Figure 11



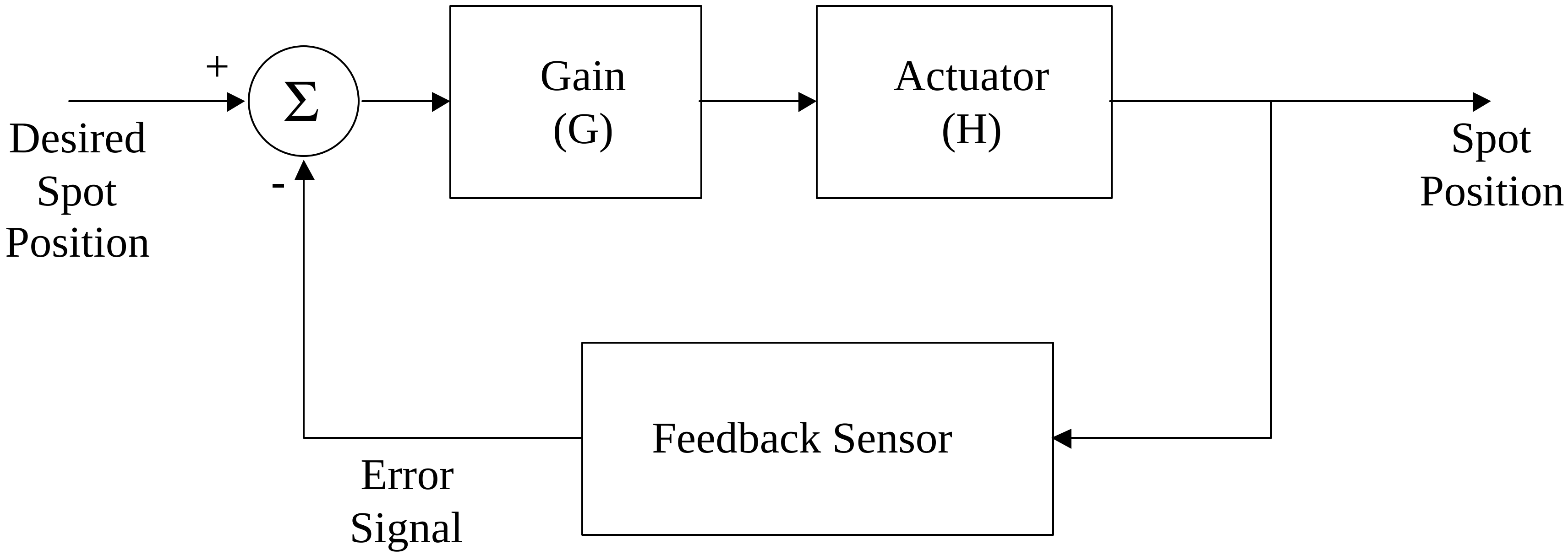
in focus

0.5 µm defocus

1.0 µm defocus

2.0 µm defocus

Figure 12


+
Σ
Desired
Spot
Position
-
Gain
(G)
Actuator
(H)
Spot
Position
Feedback Sensor
Error
Signal

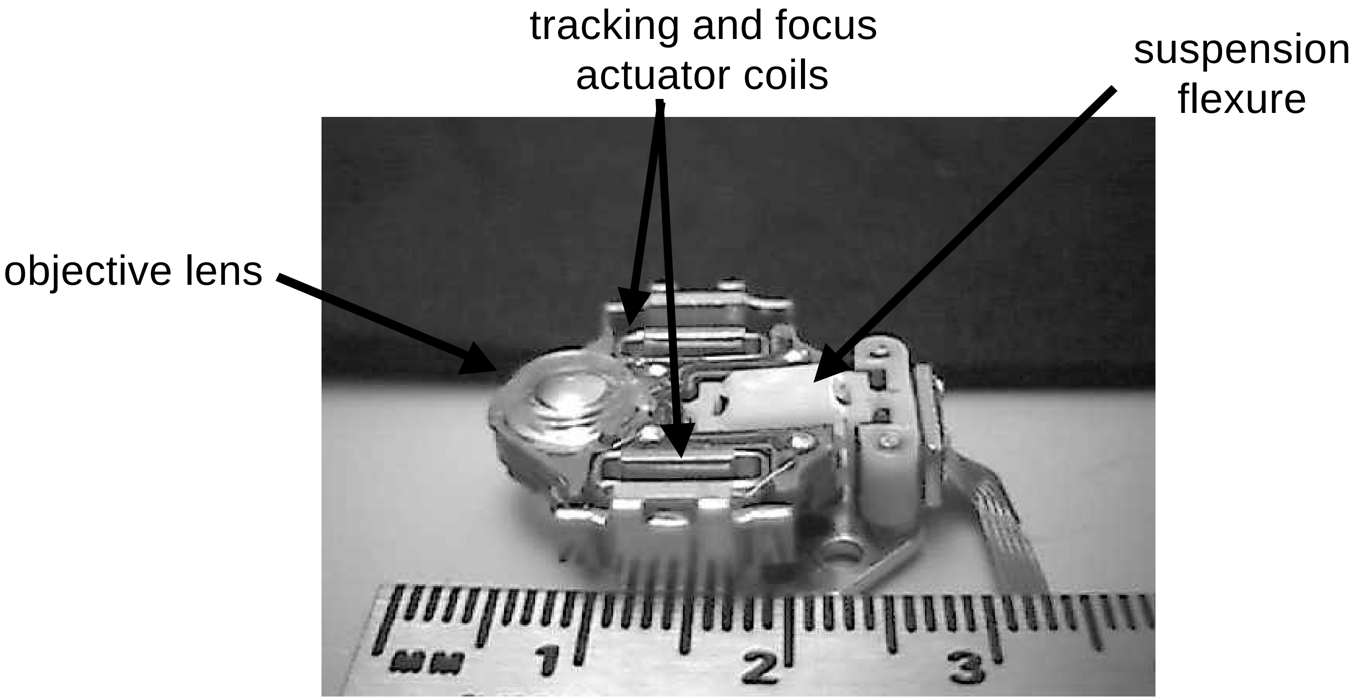

tracking and focus actuator coils
suspension flexure
objective lens
MM
1
2
3

Figure 14

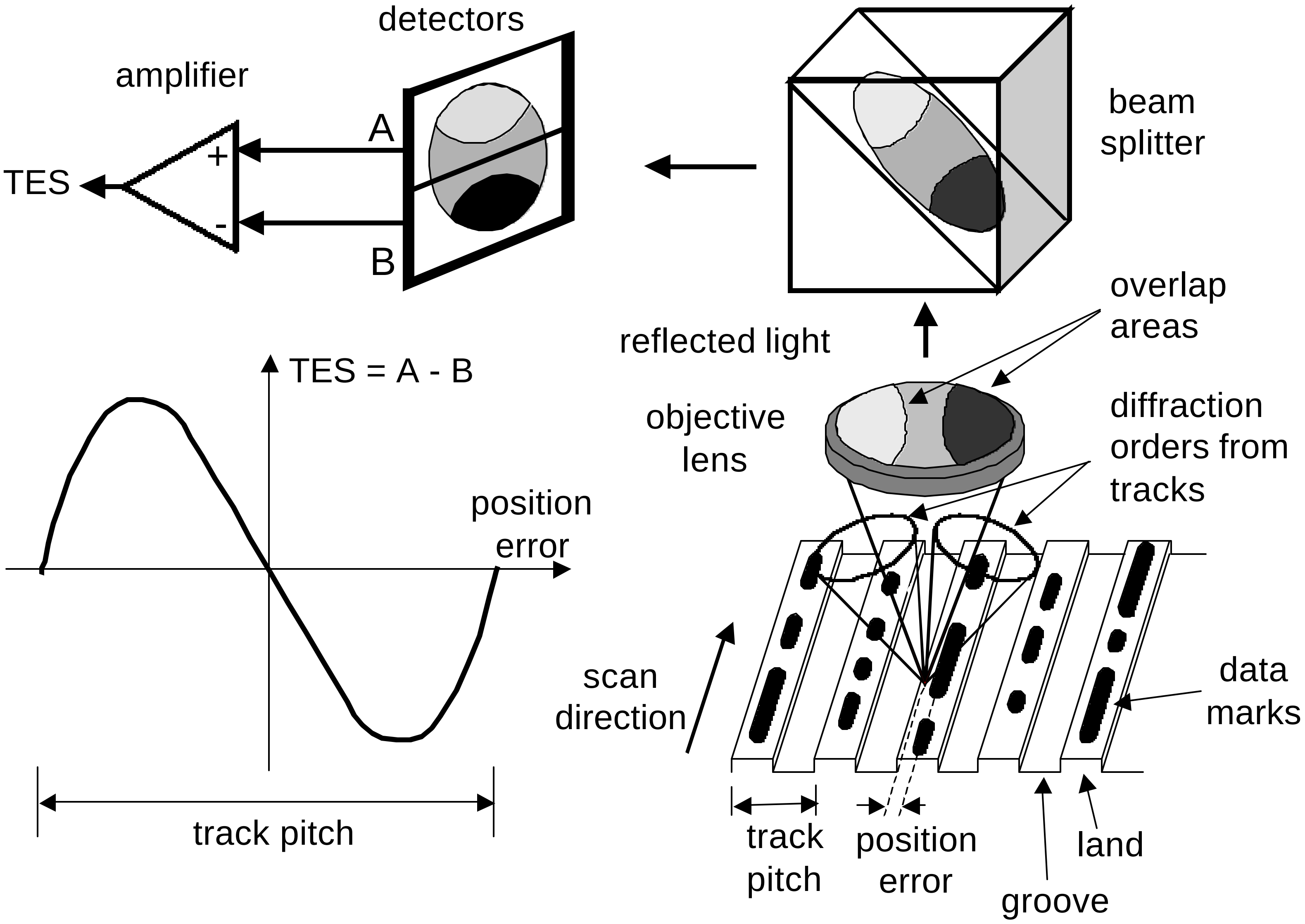
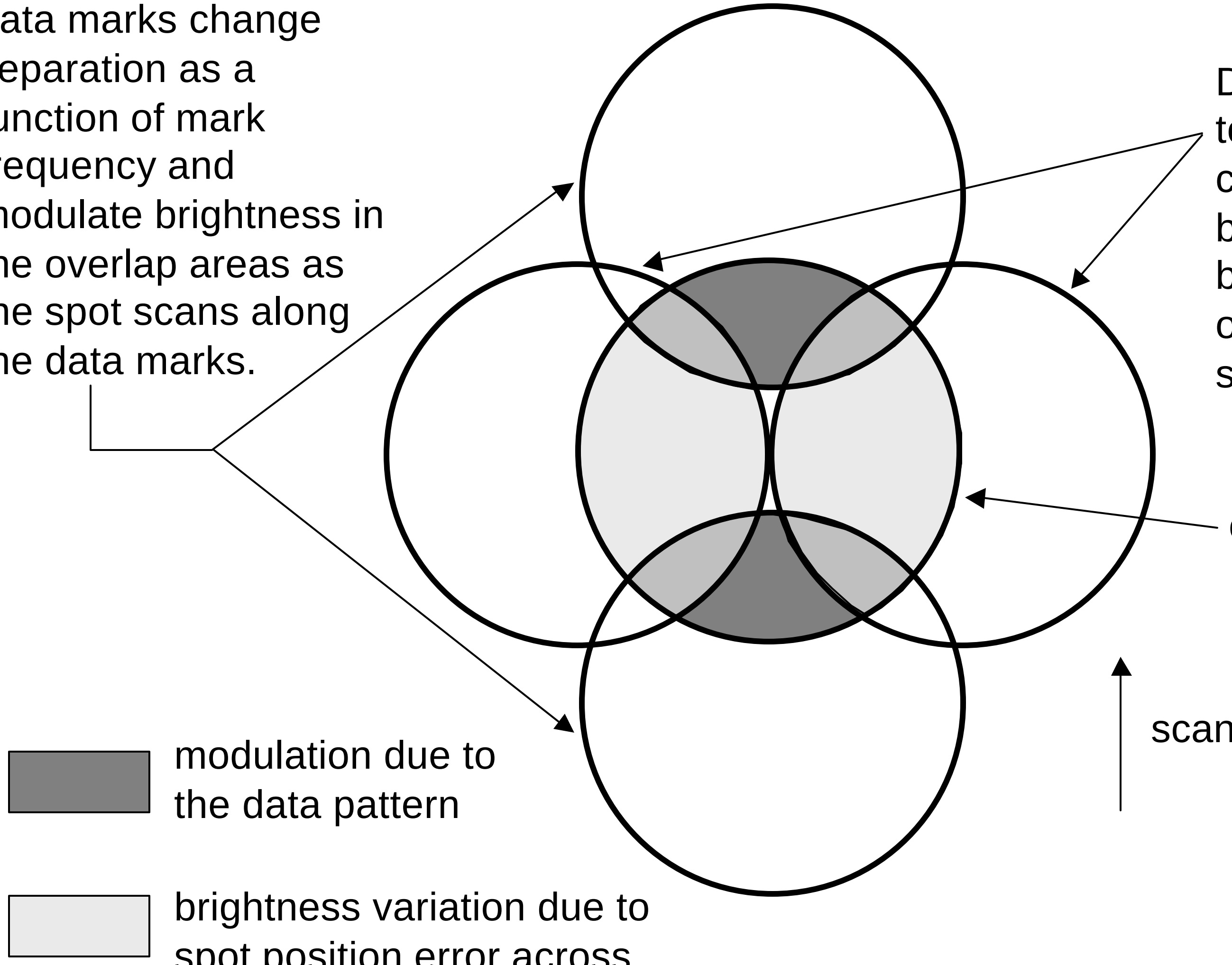

detectors
amplifier
A
+
TES
-
B
beam
splitter
overlap
areas
reflected light
TES = A - B
objective
lens
diffraction
orders from
tracks
position
error
scan
direction
data
marks
track pitch
track
pitch
position
error
land
groove

Figure 15



Diffracted orders due to data marks change separation as a function of mark frequency and modulate brightness in the overlap areas as the spot scans along the data marks.

Diffracted orders due to tracks have constant separation, but change brightness in the overlap areas as the spot moves off track.

objective lens

scan direction

■ modulation due to the data pattern

□ brightness variation due to spot position error across the track

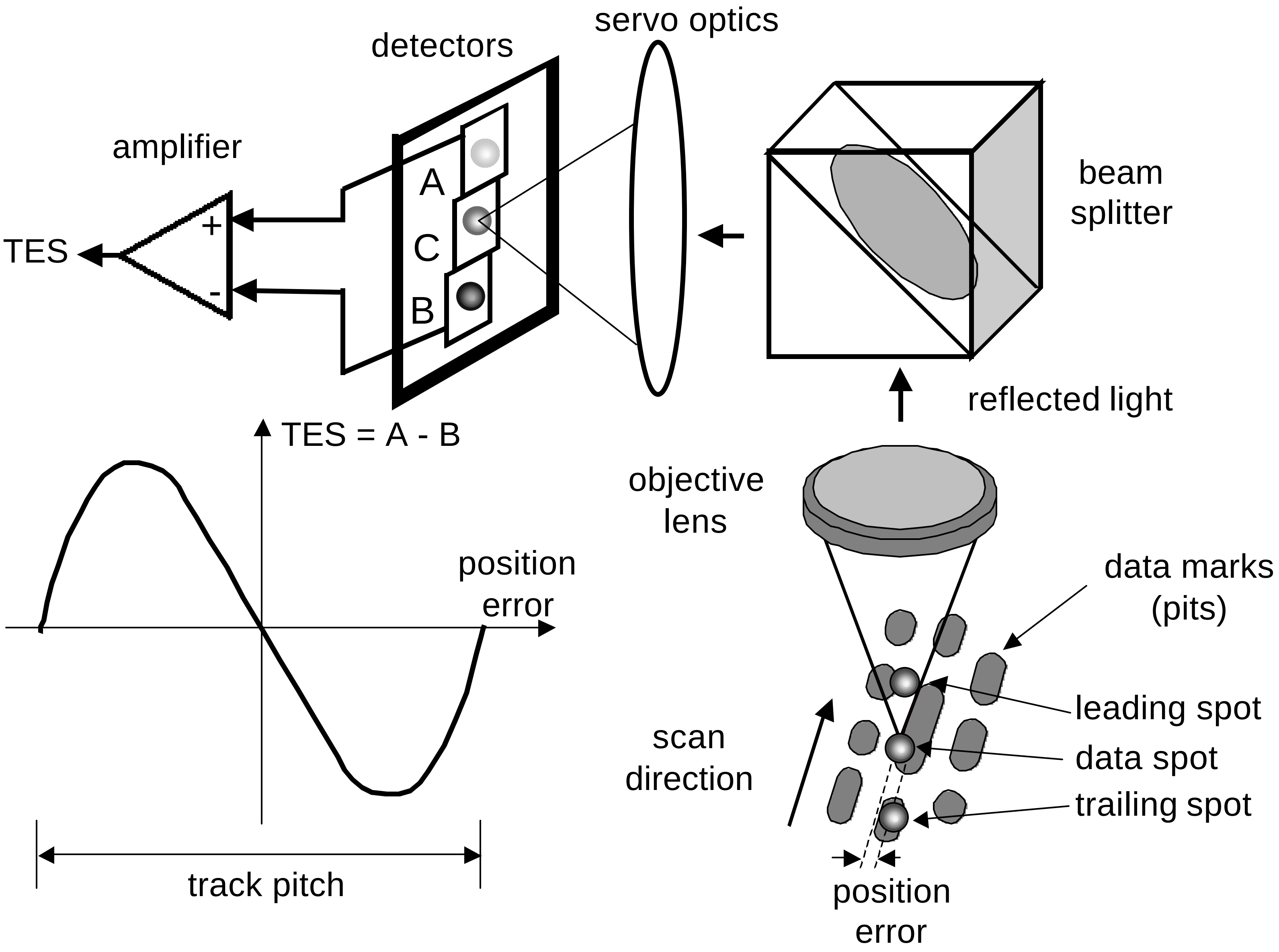


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Figure 17

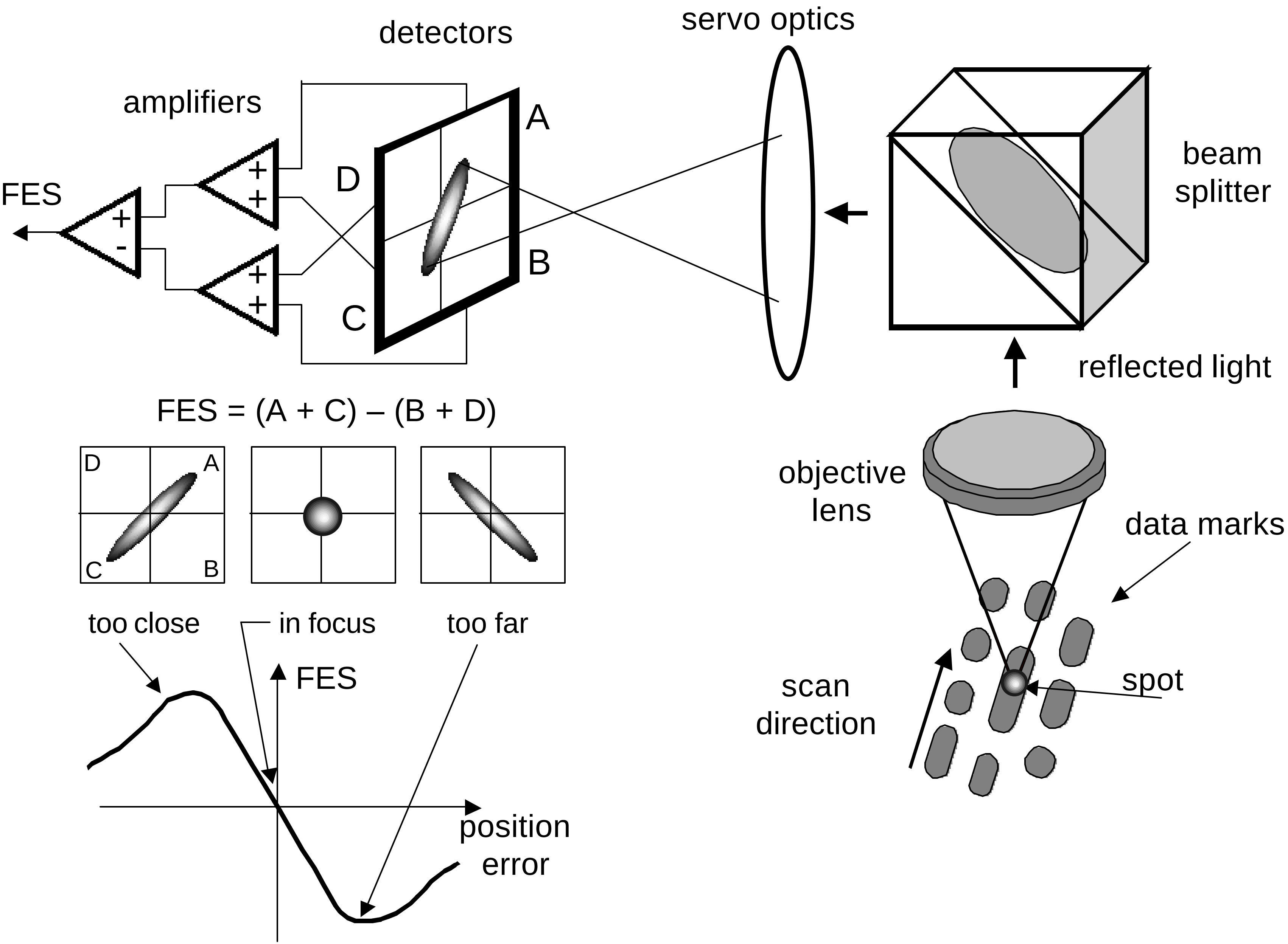
servo optics
detectors
amplifiers
A
D
B
C
FES
+
+
+
+
+
-
beam splitter
reflected light
FES = (A + C) – (B + D)
D
A
C
B
objective lens
data marks
too close
in focus
too far
FES
scan direction
spot
position error

Figure 18

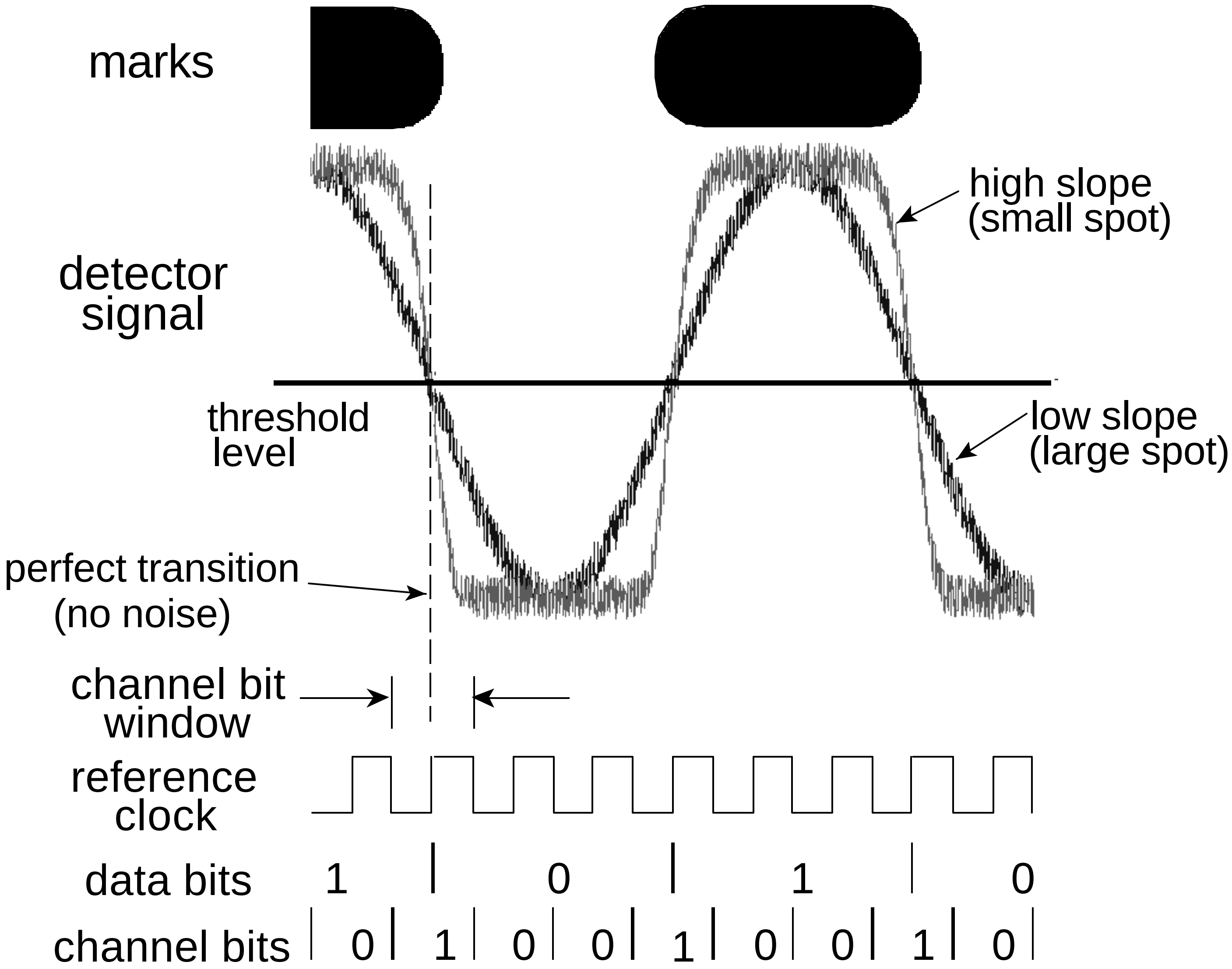

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Figure 19

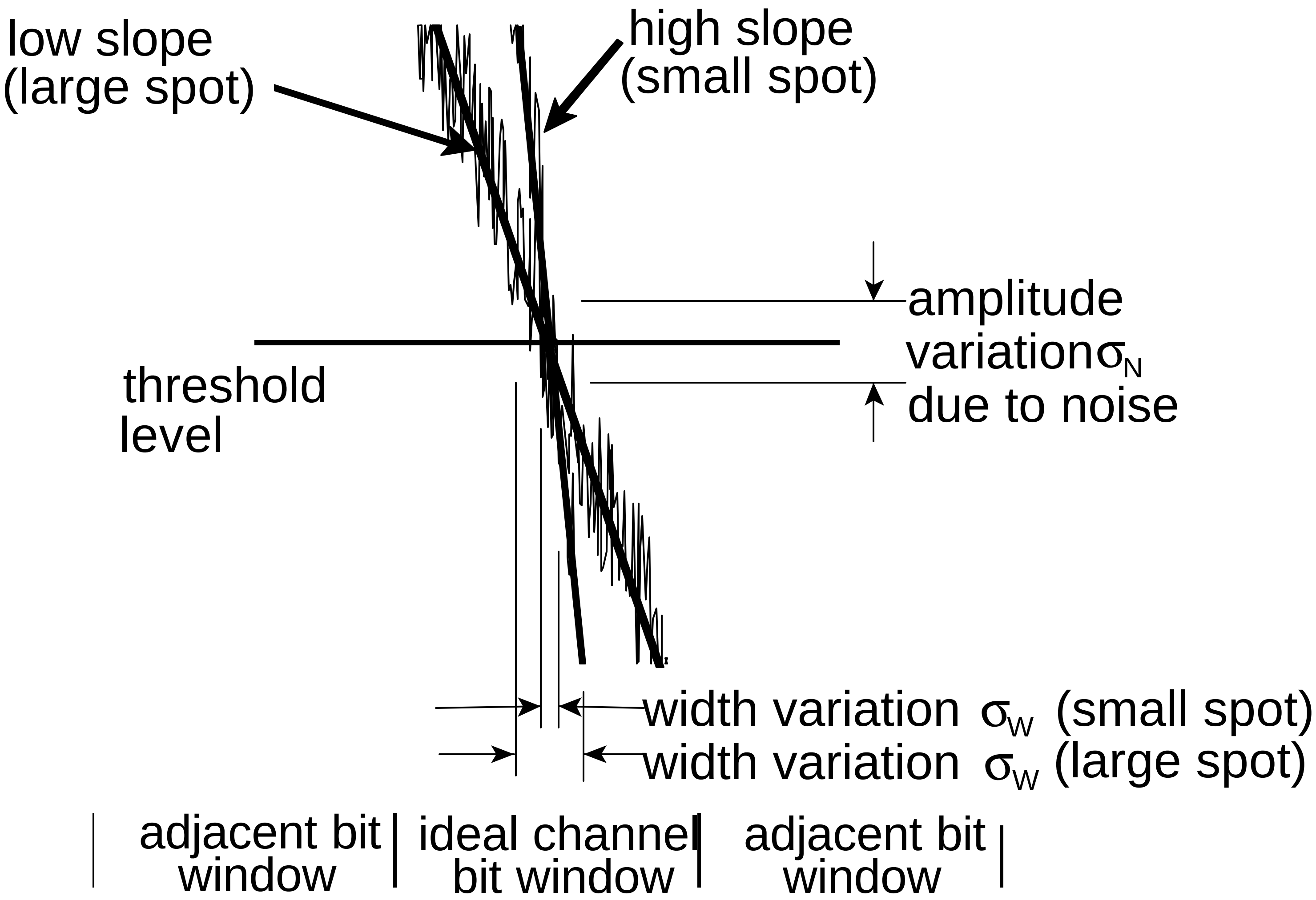
low slope
(large spot)
high slope
(small spot)
amplitude
variationσ_N
due to noise
threshold
level
width variation σ_W (small spot)
width variation σ_W (large spot)
adjacent bit
window
ideal channel
bit window
adjacent bit
window

Figure 20

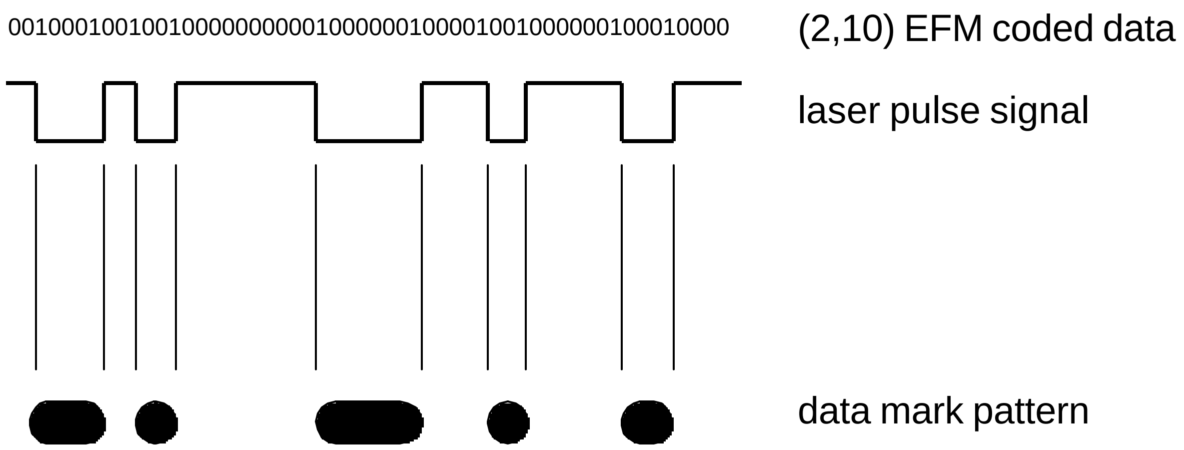

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Figure 21

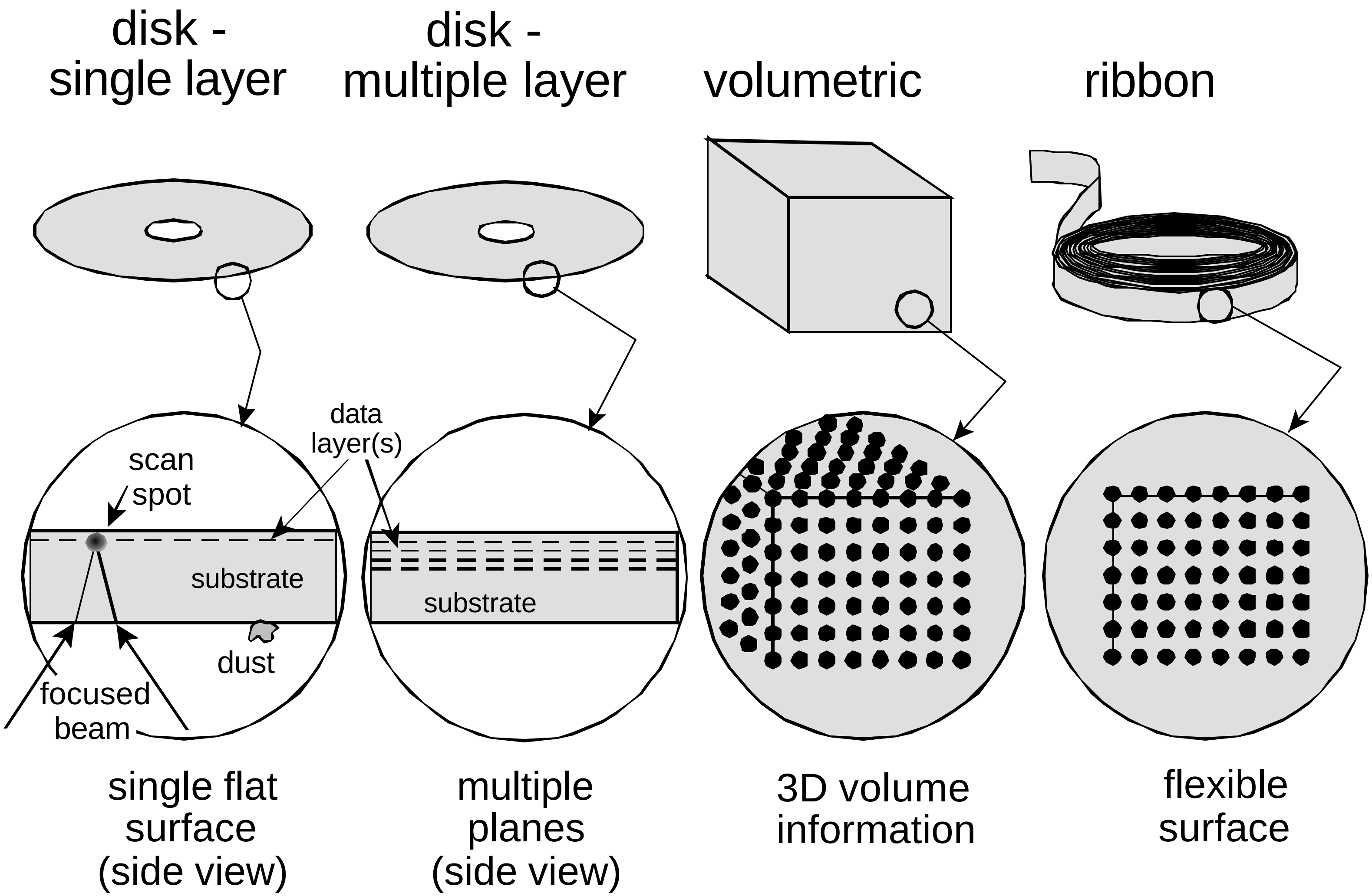
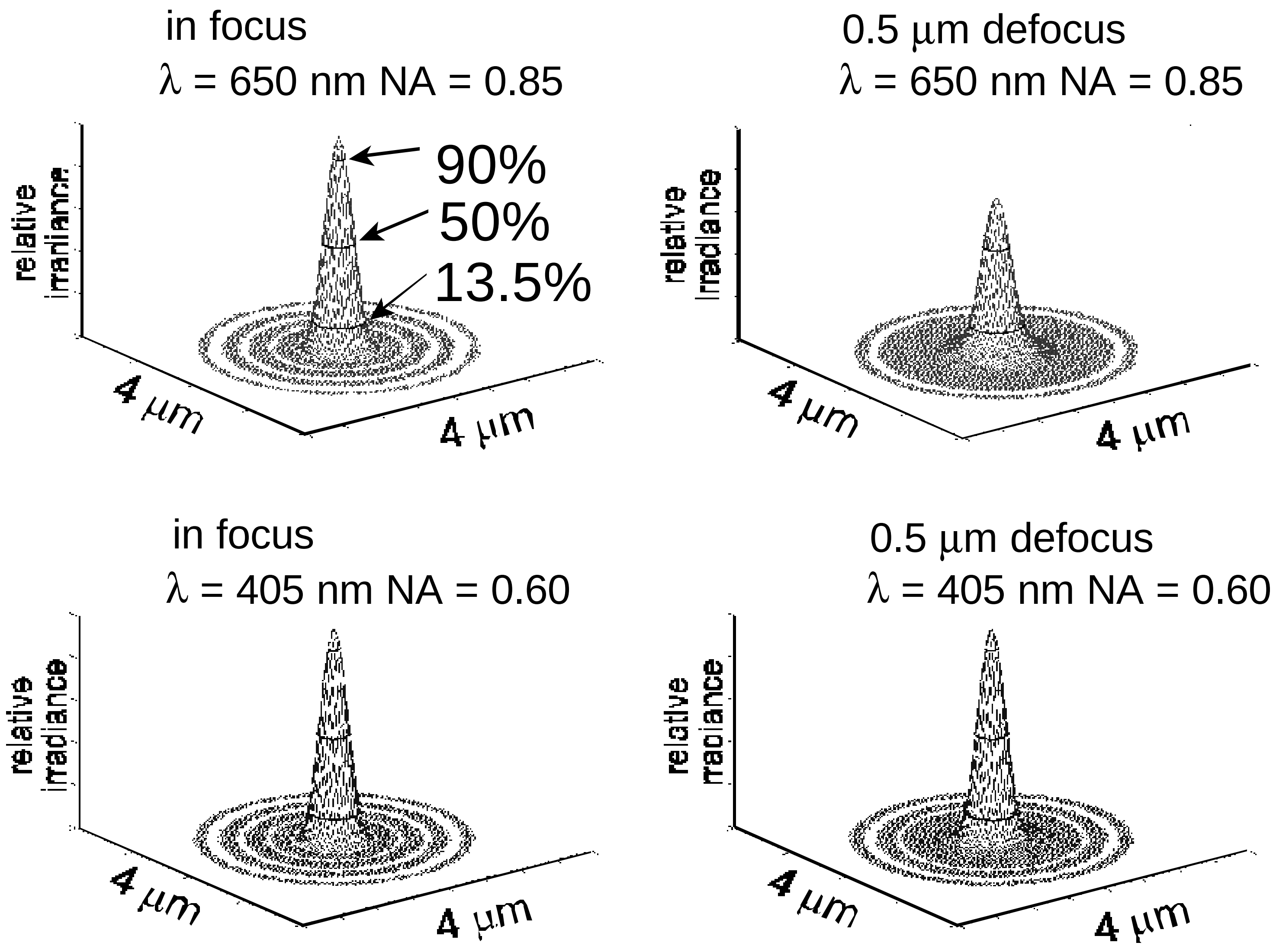

disk -
single layer
disk -
multiple layer
volumetric
ribbon
scan
spot
data
layer(s)
substrate
dust
focused
beam
substrate
single flat
surface
(side view)
multiple
planes
(side view)
3D volume
information
flexible
surface

Figure 22



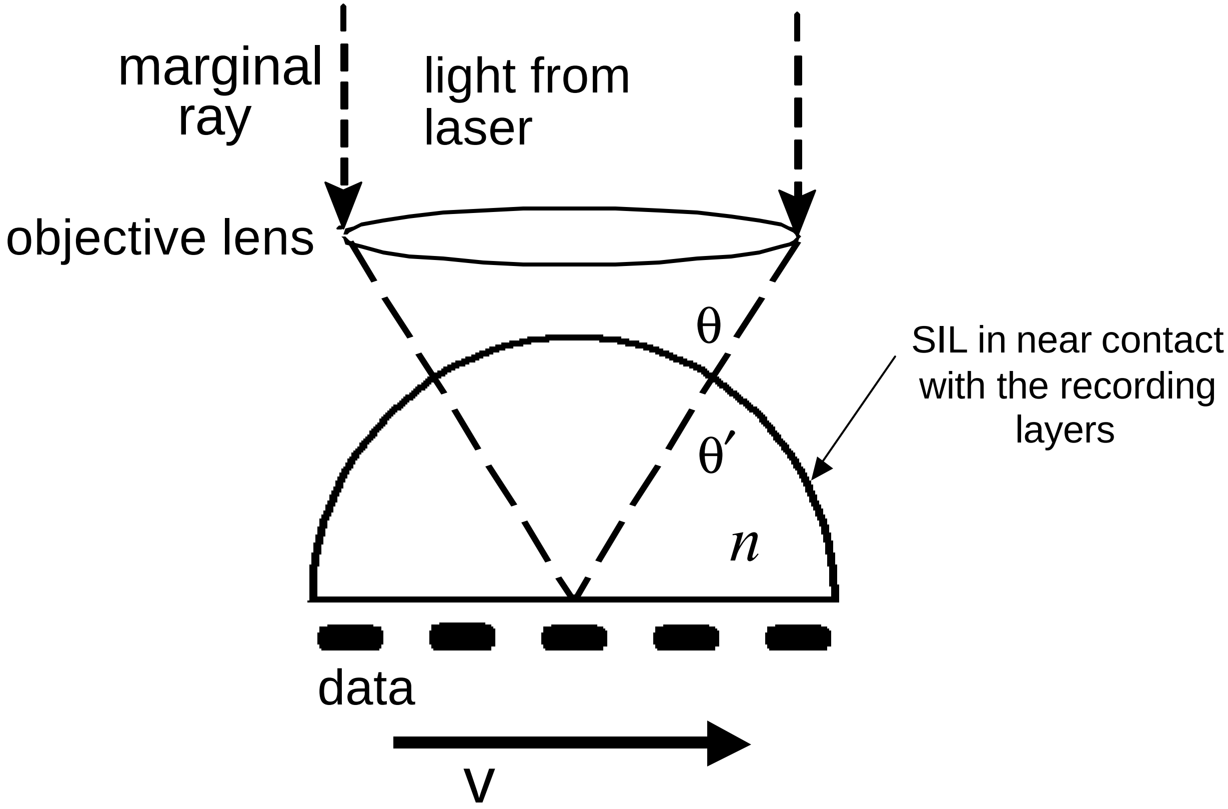
in focus
λ = 650 nm NA = 0.85

0.5 μm defocus
λ = 650 nm NA = 0.85

in focus
λ = 405 nm NA = 0.60

0.5 μm defocus
λ = 405 nm NA = 0.60

Figure 23


marginal
ray
light from
laser
objective lens
θ
θ′
SIL in near contact
with the recording
layers
n
data
v

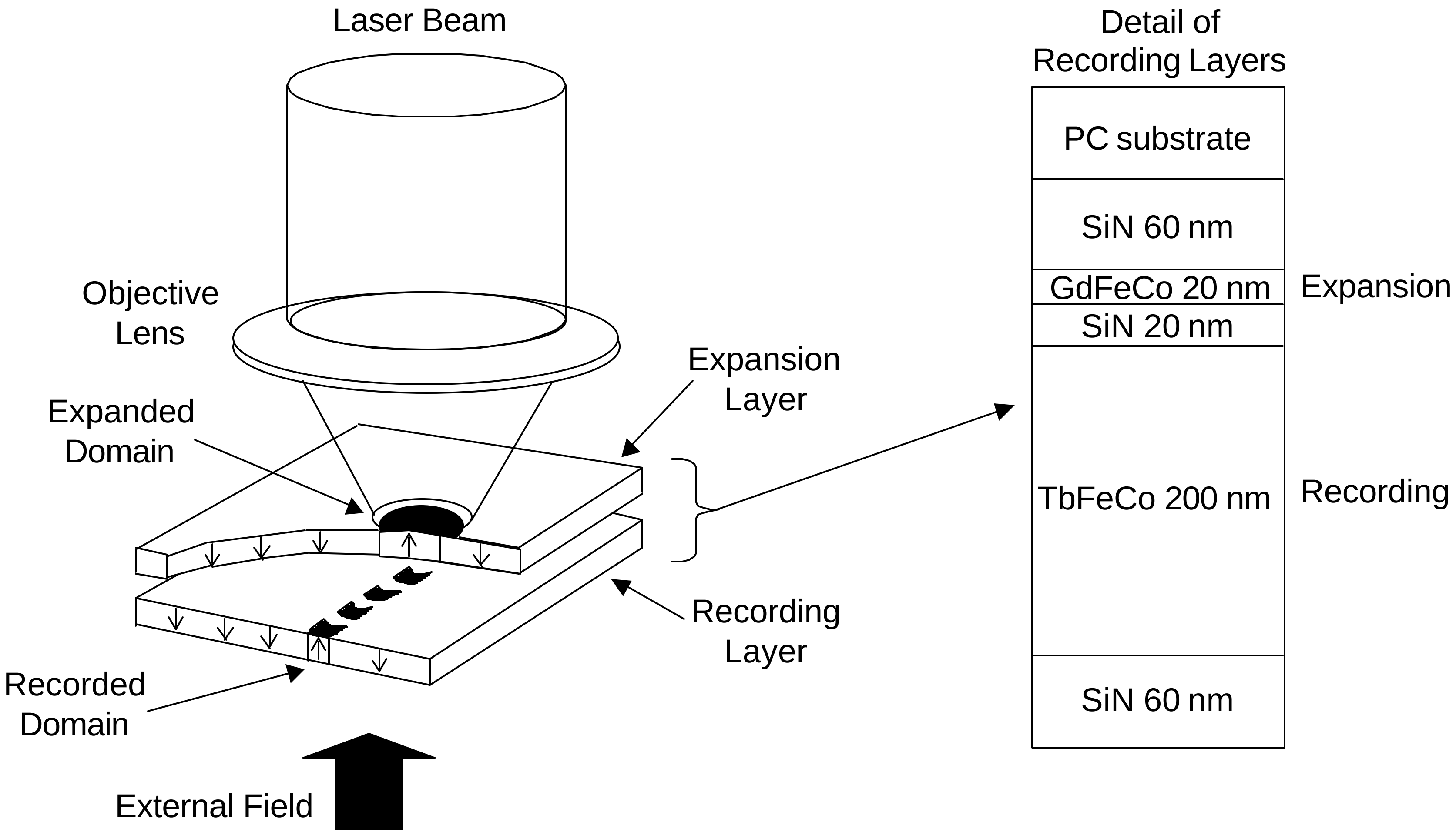

Laser Beam
Objective Lens
Expanded Domain
Expansion Layer
Recording Layer
Recorded Domain
External Field
Detail of Recording Layers
PC substrate
SiN 60 nm
GdFeCo 20 nm
SiN 20 nm
TbFeCo 200 nm
SiN 60 nm
Expansion
Recording

Figure 25