國立交通大學

光電工程研究所

博士論文

光學調變結構在容積光碟中的應用

Optical Switching Structure for High Density Volumetric Optical Storage Applications

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摘　要

為了因應電腦、多媒體與網路等科技的發展，更大的記錄容量與高速的資訊存取已成為光資訊儲存技術發展的指標。提升光碟記錄密度的方法可分成兩大類：提升光碟片的面積密度與容積密度。使用較短波長的雷射光源與較大數值孔徑(numerical aperture, NA)的物鏡可提升光碟片的面積密度。除此之外，可在垂直碟面的方向上設置多於一層的記錄面，以倍數提升光碟片的容積密度(volumetric density)，此即為容積光碟技術。本論文中提出光學調變結構(optical switching structure)應用在容積光碟中，使容積光碟中讀出層有高反射及高吸收率，非讀出層有高穿透率，因此可以在不改變雷射光波長及物鏡 NA 的條件下使容積光碟在各層中的讀寫機制能達到最佳化，如此可以有效的增加每一層光碟記錄容量。

此論文討論光學調變結構應用在重複擦拭型(rewritable type)與寫一次型(write-once type)容積光碟兩方面。論文的第一部分的研究是在於重複擦拭型容積光碟中的記錄層中加入一種光學特性(optical characteristics)對溫度敏感的光學調變結構，使得資料層受到聚焦雷射光照射時及非照射時的光學特性受到精確控制，如此便可提高雷射光使用效率，使得資料層的讀出（或是記錄）特性提昇。

此論文的第二部分討論光學調變結構及透明記錄材料堆疊的容積光碟結構，此光碟結合了寫一次型記錄媒體以及容積光碟兩者優勢，目的在於提昇寫一次型記錄媒體的容量。在此新型光碟中，當雷射光聚焦在光碟記錄層中的其中一層時，光控制層可精確控制在此記錄層的透明記錄材料上溫度變化分佈，造成此透明記錄材料表面高度變化而形成次微米至奈米級記錄信號，如此便可作為高容量多層可記錄式資料儲存媒體。也因為透明記錄材料具有極高的雷射光穿透特性，加上利用光控制層提昇雷射光能量的使用效率，因此在光學讀寫頭僅提供有限雷射光能量的條件下，可以大幅增加光碟中的資料層數目，使得在一基板上的光碟容量得以提昇。此外，此光碟結構亦有製作簡單，相容於現有光學讀取頭架構的優點，故有很廣的應用層面。

Optical Switching Structure for High Density Volumetric Optical Storage Applications

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Abstract

Optical data storage industries are continually growing with progress of computer, multimedia, and network markets. In this trend, technologies capable of recording more information thus become increasingly demanded.

The advanced optical storage technologies can be categorized into two groups: one is to increase the areal density of a single-layer optical disk by employing narrow track-pitch, short wavelength laser, and high numerical aperture (NA) objective lens; the other is to multiply the volumetric density of a three-dimensional volumetric optical disk by implementing multiple recording layers along the direction perpendicular to the data surface. The thesis is devoted to increasing the volumetric density by employing optical switching structure in multilayer optical disk.

For reading/recording on a lower targeted recording layer of rewritable type volumetric optical disks, transmitted laser power is decreased by absorption and reflection of the upper layers. Thus, a layer of thermo-chromatic material has been added as an optical switching structure next to the recording layers to modulate the optical characteristics of the recording layers by the diffraction limited laser beam during writing. Experimental results showed that the peak writing power could be reduced by 42% in the disk with an additional optical switching structure. Thus, optical switching structure is promising for rewritable type volumetric recording to optimize the reading/recording performance of the volumetric disk.

A write-once type volumetric optical disk having multiple transparent films with optical switching structure was demonstrated as a recording medium to increase the number of recording layers. In the disk, the optical switching layer was adopted to reduce laser energy decay and increase reading and recording sensitivity. Well-defined marks of about 100 nm in depth can be yielded precisely on the transparent films by a focused laser beam. Writing and reading of a four-layer recordable disk, fabricated by molding and spin bonding techniques, were demonstrated experimentally. Furthermore, by adoption other advanced techniques such as signal processing, parallel accessing, and MOEMS (micro opto-electro-mechanical system) pickup head, the proposed disk is projected to have a capacity over 1 trea-bit.

誌　謝

六月，鳳凰花開的季節。轉眼間，加入謝漢萍教授的研究群已經六年了。在完成博士論文的時刻，感謝在這六年來對我悉心指導、諄諄教誨的謝漢萍教授，謝教授不僅在專業的學術領域研究上讓我獲益匪淺，也讓我有機會到國內外的企業或是研究單位實習，使我開闊了視野。當謝教授的研究生，我收穫滿滿。

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徐徐和風，田田荷葉，電資大樓前的荷花池顯得分外恬靜，只剩枝葉婆娑裡知了正在高聲鳴唱，彷彿正迎接下批新學子的到來。終須一別，衣袖的長度卻不容我仿效徐志摩的瀟灑，雲彩片片，已長留我心。此行不虛！

民國九十三年六月
于　電資大樓

吳豐旭

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CHAPTER 1

INTRODUCTION

The principles of the optical data storage including read-only memory (ROM), write-once read-many (WORM) and rewritable systems are presented in the beginning of this chapter. After a short overview, some critical issues with respect to the optical pickup and the disk are considered. Next, the high density recording techniques in reducing the size of the optical pickup and the overall form factor of the drive and disk are introduced. Finally, the motivation and organization of this dissertation are presented.

1.1 Overview of Optical Storage

Optical storage systems consist of a drive unit and a storage medium in a rotating disk form. In general, the disks are pre-formatted using grooves and lands (tracks) to enable the positioning of an optical pickup to access the information on the disk. Under the influence of a focused laser beam emanating from the optical head, information is recorded on the media as a change in the material characteristics (often using a thermally induced effect). To record a bit, a small spot is generated on the media modulating the phase, intensity, polarization, or reflectivity of a readout optical beam which is subsequently detected by a detector in the optical head. The disk media and the pick-up head are rotated and positioned through drive motors and servo systems controlling the position of the head with respect to data tracks on the disk. Furthermore, additional peripheral electronics are used for control and data acquisition and encoding/decoding, as illustrated in Fig. 1.1.1.

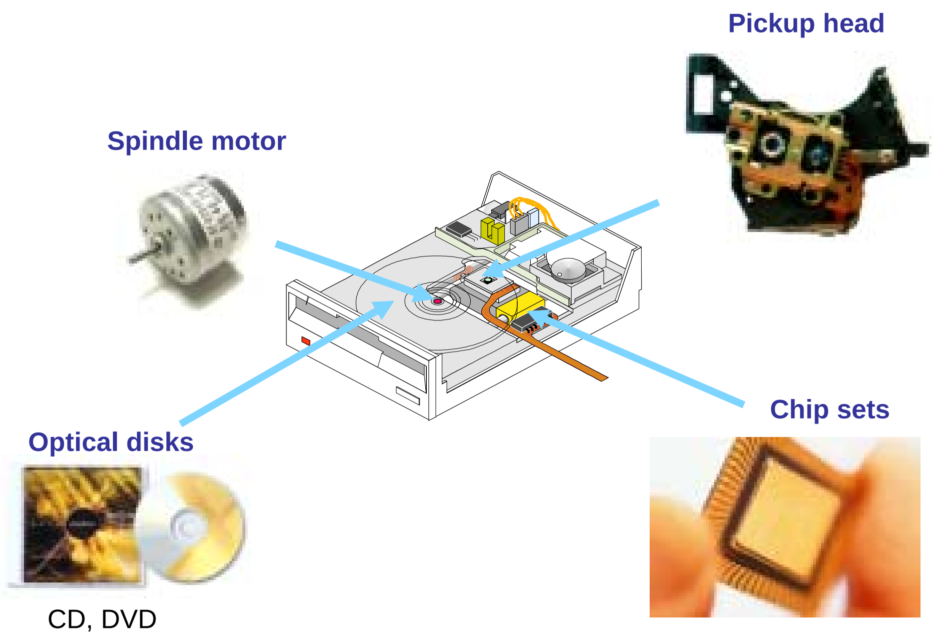


Fig. 1.1.1. Key components of an optical disk system, including spindle motor, pickup head, chip sets, and optical disks.

As for all storage systems, the storage capacity, data transfer rate, access time, and cost characterize optical disks systems. The storage capacity is a function of the spot size and the physical dimensions of the media. The areal density is governed by the resolution of the media and by the numerical aperture (NA) of the optics and the wavelength (λ) of the laser in the optical head used for recording and reading. The areal density can be limited by how well one can position the head over the tracks. The track density (tracks/inch) is used as a metric for this characteristic. In addition, the areal density can be limited by how close the optical transitions can be spaced. The data transfer rate is critical in applications such as long data streams must be stored or retrieved in image storage or back-up applications. The linear density, the rotational speed of the drive, and the number of pickup heads determine data rate. It is often limited by the optical power available, the speed of the pickup head servo controllers, and the tolerance of the media to high centrifugal forces. The access time is another critical parameter in computing applications such as transaction processing and represents how fast a data location can be accessed on the disk. It is mostly governed by the latency of the head movements and is proportional to the weight of the pickup head and the rotation speed of the disk.

Optical storage offers a reliable and removable storage medium with excellent robustness and archival lifetime and with very low cost. A key difference between optical recording and magnetic recording (such as hard disk drive, HDD) is removability. Both optical recording and readout can be performed with a head positioned relatively far away from the storage medium, unlike magnetic hard drive heads. This allows the medium to be removable and effectively eliminates head crashes, increasing reliability. In addition, during recording, optical radiation is used as a focused thermal source allowing the use of more stable materials suitable for archival lifetimes. However, the remote optical head is heavier and leads to slower access times compared to hard disk drives.

Consequently optical storage has remained limited to market segments required removability and reliability that are not well served by magnetic hard disks. Typical applications involve archival storage, including software distribution, storing digital photographs, information appliances (such as recording movies), other video materials, and multimedia presentations at home and business, and online databases including video servers. More recently, the magnetic tape market for video camcorders and VCRs (video cassette recorder) has also been targeted.

These types of applications, while benefiting from random access capabilities of disk systems, are less sensitive to access time requirements but require low cost and high capacity removable storage. The compact disk rewritable format (CD-RW) and recently the digital versatile disk format (DVD±RW, DVD-RAM) based on phase change media are designed to best satisfy these requirements. By thermally heating at different rates, a laser beam can record bits of information by locally changing the reflectivity of the medium. With the CD and DVD formats, the information is recorded in a spiral while the disk turns at a constant linear velocity, thus maximizing data capacity at the expense of transfer rate. The CD format used a 12 cm standard disk which offers a typical capacity of 650 MB with an average seek time (access time) in the order of 80 ms and maximum data rate of about 7,800 kbps (bit per second) currently (52X CD-ROM). Few years later, the DVD format offers 4.7 GB capacity, 21,600 kbps data rate and 95 ms average access time (16X DVD-ROM) by using a smaller spot size (from a shorter wavelength laser and a higher NA lens), higher power lasers, more powerful error correction codes, and faster servo systems. Besides, one pickup head is also capable of recording and reading multiple storage layers, thus increasing the capacity to 9.4 GB in a dual layer DVD (DVD-9 format) disk.

Magneto-optic (MO) storage systems record data by thermally heating (with the laser spot) the media under the influence of a magnetic field. Data are recorded by re-orienting magnetic domains within the heated spot. During readout the polarization of the laser beam is modulated by the orientation state of the magnetic domains. Until recently, all systems using magneto-optic media used a standard format to shorten the access times (at the expense of capacity) and approaching hard disk like speed performance with a removable media. With standard formatted systems the disk turns at a constant angular velocity and data are recorded on concentric tracks as in magnetic hard drives. While reading the inner or outer tracks the speed of rotation remains constant, allowing for faster access times. However, this format results in constant number of bits per track, limited by the number of bits that can be supported by the most inner track, and wastes valuable real estate on the outer tracks. To eliminate this waste, a "banded" format is now used where tracks of similar length are grouped in bands, allowing the outer bands to support much larger number of bits than the inner bands. This, however, requires different channel codes for the different bands to achieve similar bit error rates over the bands. Today, removable MO systems provide 640 MB capacity with 3.5 inch diameter disks with speed performance comparable to hard drives.

In contrast to non-removable media, for removable storage, annual increases in capacity are not necessarily desirable. For example, DVDs took the place of CDs, entered the market decades ago, until recently. This is because removable storage media are tightly constrained by standards that are established for compatibility. Removable storage manufacturers instead introduce products at an entry capacity and performance point that is desirable for a particular data type. Thus, the optical storage market is essentially driven by applications rather than by progress made in technology. Therefore, projections made on optical storage critically depend on application roadmaps [1-1] such as the one shown in Fig. 1.1.2.

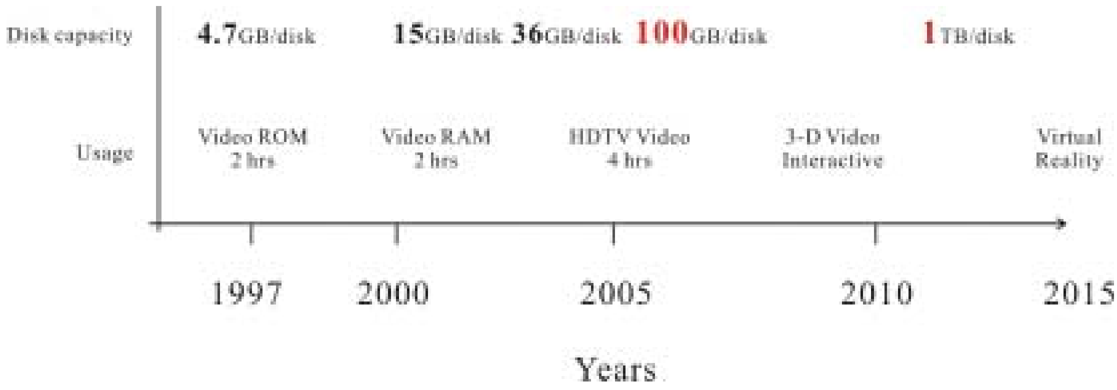


Fig. 1.1.2. Potential evolution of application requirements for removable storage.

1.2 Basic Description of the Optical Data Storage Technology

1.2.1 Recording and Readout of Information on Optical Disks

Storage and retrieval of data are two primary aspects associated with optical data storage technology. The process for storing data marks on a recordable optical disk is shown in Fig. 1.2.1, where an input stream of digital information is converted with an encoder and modulator into a drive signal for a laser source. Next, a modulated intense light beam, emitted from a laser source, is directed and focused onto the surface of storage medium with illumination optics. As the storage medium moves, energy absorbed from the focused spot heats up a small, localized region and changes the optical properties of the storage medium, a data mark is written. The size of the data mark is nearly the size of the focused laser spot. Due to the physics of diffraction, the spot size s is limited. Instead, it is a function of the wavelength of the laser (λ), the focusing properties of the objective lens, system aberrations and the thin-film structure used as the recording layer [1-2]. A simple relationship used to estimate the full-width at half maximum (FWHM) spot size for conventional Gaussian illumination is:

$$\Delta x = 0.6\frac{\lambda}{NA} = 0.6\frac{\lambda}{\sin\theta} \tag{1-1}$$

Where λ is the wavelength in the air, NA is the numerical aperture of the system, n is the refractive index of the medium, and θ is the marginal ray angle.

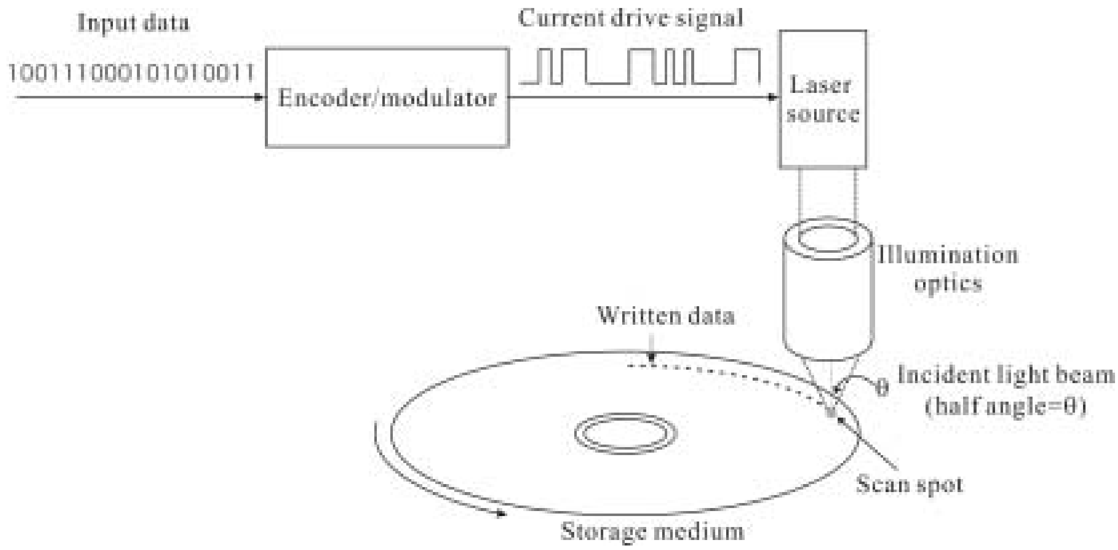


Fig. 1.2.1. The process of recording data onto an optical disk starts with the user input data stream converted to a current drive signal for the laser diode. Intense pulses from the laser cause physical changes in the surface of the recording medium and result in spiral tracks of data marks as the disk spins.

The laser is used at a low constant output power for preventing heating the data surface beyond its thermal writing threshold when retrieval of data marks on the disk. For the light path, laser beam is directed through a beam splitter into the illumination optics and focused onto the surface. As the data marks to be read pass under the scan spot, the reflected light is modulated. The modulated light is collected by illumination optics and directed by the beam splitter to servo and data optics, then focused onto detectors. The detectors transform light modulation into current modulation that is amplified and decoded to produce the output data stream. The readout model is illustrated in Fig. 1.2.2.

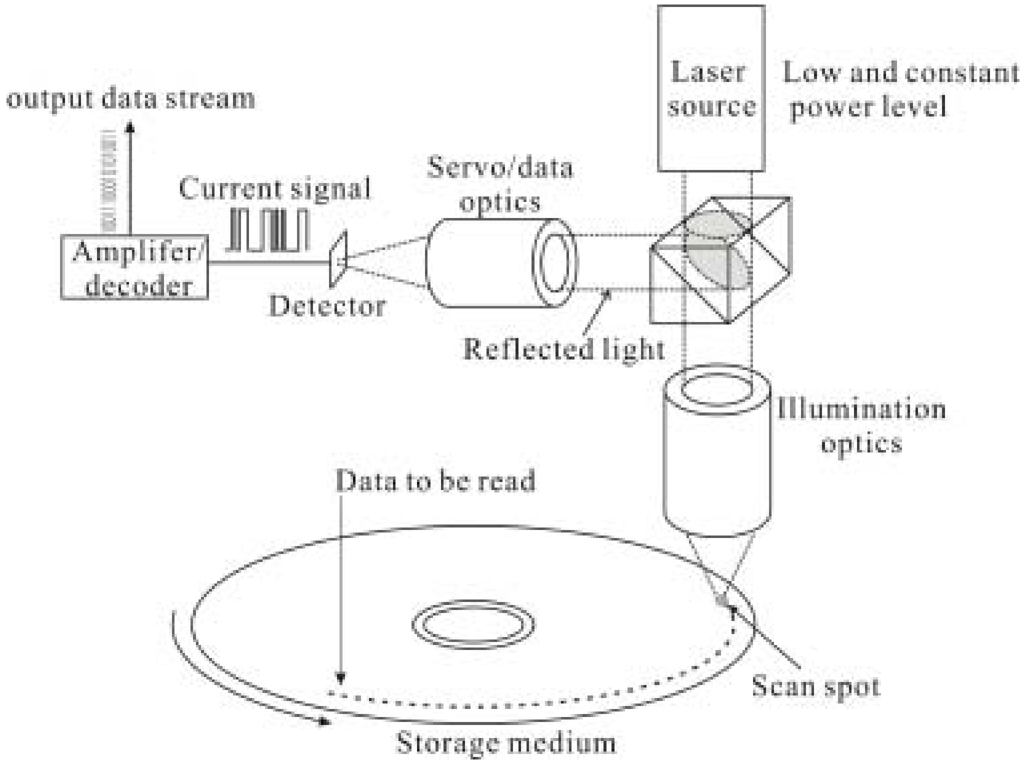


Fig. 1.2.2. A constant, low power laser beam scans a data track to readout data from the disk. Reflected light is modulated by the data-mark pattern and directed to servo and data detectors to convert the light modulation in a current signal with a beam splitter.

The data capacity of an optical disk is proportional to $1/s^2$. Therefore, to increase the data capacity, reduce λ, increase NA or introduce multiple layers of data marks. Multiple layers increase the data capacity by N, where N is the number of layers.

1.2.2 Media Substrates

The size of the recorded marks of the optical storage media is about 1.0 μm^2, which is much smaller than the sizes of the ordinary dust particles and other airborne contaminations. Two distinct situations occur without additional protection: either scratches or fingerprints perturb the incident wave front (phase errors), or large dust particles obscure the incident beam (amplitude attenuation). To circumvent this problem, a substrate is used to protect the recording layer from the environment, as illustrated in Fig. 1.2.3.

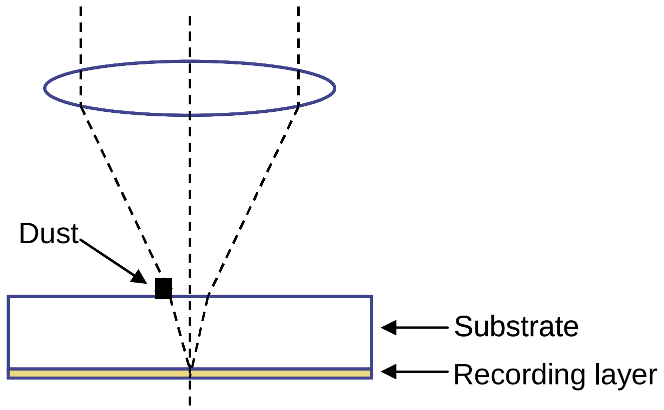


Fig. 1.2.3. Separation of the recording layer from environmental effects.

For example of CD-type storage, the substrate thickness should be at least hundred micrometers. With the NA used in a CD player, this corresponds to a certain beam diameter or footprint on the blank side of the disk (typically 700 μm diameter with substrate thickness of 1.2 mm). Since the comatic aberration of readout spot introduced by disk tilt is proportional to $t \cdot NA^3$, where t is the substrate thickness, the thinner substrates t are probable with higher NA in increasing recording density. However, the substrate should not be too thin for mechanical rigidity consideration. Thus, newly developed DVD format defines substrate of 1.2 mm again, but the thickness is divided over two substrates and glued back to back, the effective substrate thickness at readout spot is then reduced to 0.6 mm.

1.2.3 The Light Source

All optical recording technologies rely on lasers as their source of light. The lasers used in optical disk and tape data storage are semiconductor laser diodes of the shortest possible wavelength that can provide sufficient optical power for read/write/erase operations over a period of several thousand hours. Presently the shortest wavelength available in moderate power lasers (around 50 mW) is in the neighborhood of 650 nm; these lasers are being used in DVD±R, ±RW, -RAM, MO, and PC products. For CD and DVD applications where writing is not a concern, low power lasers (e.g. 5 mW) which emit at 630 nm and 650 nm are being considered. The emphasis on short wavelength lasers for optical recording applications is due to the fact that shorter wavelengths can be focused to smaller spots at the diffraction limit. All things being equal, the diameter of a focused spot scales with its wavelength: a reduction of the wavelength by a factor of 2, for example, will result in a reduction of the focused spot diameter by the same factor and, consequently, a fourfold increase in the data storage density can be realized.

The wavelengths of optical data storage have continuously shrunk in the past 15 years; starting at 830 nm, they are now down to 650 nm, and there is every indication that they will continue to shrink in the foreseeable future. Nichia Chemicals Corporation's 60 mW blue lasers operating in the wavelength range of 370 nm to 420 nm are now available in the market [1-3]. Several other Japanese companies (e.g., Sony, Matsushita, Pioneer, and HC Photonics [1-4]) have demonstrated the feasibility of small, inexpensive, second harmonic generation (SHG) green and blue lasers for use in optical disk drives.

Compact and inexpensive laser diode that can be incorporated into small, low-cost drives is needed for optical data storage. The power requirement from such lasers is several milliwatts for read-only media and several tens of milliwatts for recordable media. The lasers should be capable of direct modulation (e.g., by modulating the electrical current input to the laser), otherwise the cost and the size of external modulators may become prohibitive. Spatial coherence and single transverse-mode operation is a requirement, because the beam must be focused to diffraction limit. (In this context vertical cavity surface emitting laser diodes (VCSELs) as well as arrays of such lasers need to be improved, since, at high powers, these lasers tend to operate in high-order modes. Low-noise operation is very important, especially in applications such as magneto-optical readout, where signal-to-noise ratio is at a premium.

Although operation of laser diodes in several longitudinal modes is presently acceptable, for future devices it may be important to add operation in a single, stable, longitudinal mode to all their other desirable characteristics. Mode hopping, wavelength shifts of several nanometers with temperature fluctuations and with operating current, manufacturing variability of the wavelength from batch to batch, etc., are so severe that, at the present time, it is not possible to consider the use of diffractive lenses either for the collimator or for the objective lens. These high *NA*, diffraction-limited lenses are still produced by molding of glass elements. In the future, when miniaturization becomes a necessity and lenslet arrays begin to appear in commercial products, operation of the laser in a single, stable, longitudinal mode may be required.

Practically all semiconductor diode lasers used in optical storage products come from Japan. Hitachi, Sharp, and Toshiba are the leading producers of semiconductor lasers, and Nichia Chemicals is in a position to dominate the market in the area of GaN-based short-wavelength (green/blue/ultraviolet) lasers. In the United States there are pockets of excellence and know-how both in the industry and the universities.

Spectra Diode Laboratory (SDL), OptoPower and Ortel are manufacturers of specialty laser diodes in the US. Lucent Technologies and Motorola, among others, have significant programs in laser diode arrays and VCSELs. But, by and large, the major source for inexpensive laser diodes is outside the United States.

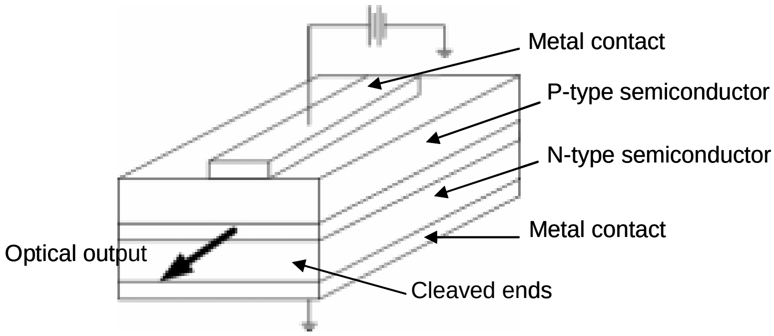


Fig. 1.2.4. Typical double heterostructure laser diode.

1.2.4 Optics in Optical Recording System

The optical path is designed to maximize the signal-to-noise ratio of the data detection and to provide robust tracking and focusing servo signals. These goals must be traded off with optical efficiency, cost, and complexity. The typical optical path for the rewritable phase-change (PC) system is shown in Fig.1.2.5. In PC recording, the polarization beam splitter (PBS) and quarter-wave plate provide an optical circulator that passes all of the linearly polarized light from the laser diode to the disk but redirects all the reflected light to the data and servo detectors.

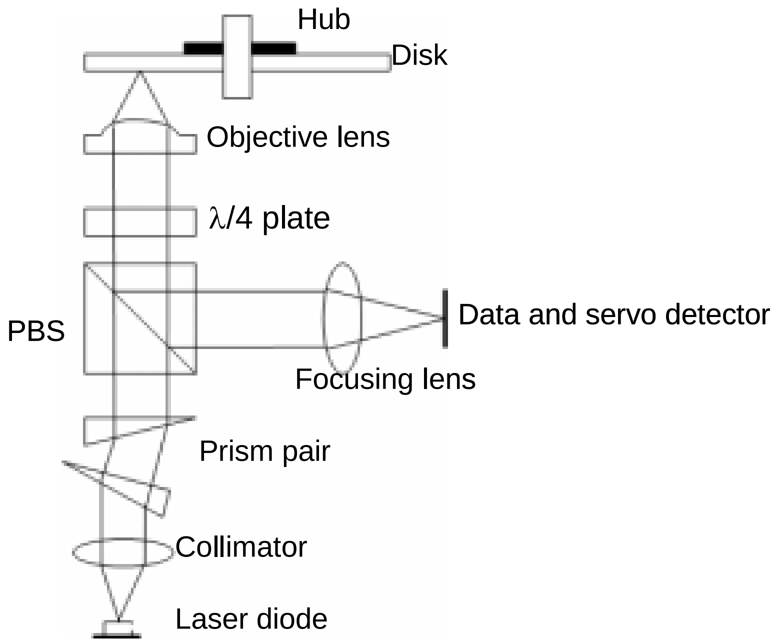


Fig. 1.2.5. Optical path for a phase-change storage system.

1.2.5 Objective Lens

The collimated and circularized beam is focused on the recording media using an objective lens in the current optical storage systems. Conventionally, the objective lens is made of molded glass or plastics. The numerical aperture of the objective lens, together with the laser wavelength λ, defines the focused spot size on the recording layer. Smaller spots yield higher density of the recorded data. Spot size FWHM is approximately given by $\Delta x \cong 0.6\lambda/NA$. Therefore, the smaller possible spot can be achieved by increasing NA of the objective lens. However, depth of focus is $\Delta z \cong \lambda/NA^2$, so large NA's decrease the depth of focus and make the axial control of the objective lens more critical. Today's commercial devices (DVD system) use $NA = 0.6$, $\lambda = 0.65$ μm, thus the spot size $\Delta x \cong 0.65$ μm and the depth of focus $\Delta z \cong 1.6$ μm. Due to large NA and focusing through CD's 1.2 mm substrate (DVD: 0.6 mm), the objective lens usually has aspherical surfaces on both sides.

1.2.6 Compatibility Issues for DVD/CD System

The prerequisite for achieving a diffraction-limited spot is that the various aberration terms of the lens system should be as small as possible. However, since the difference in substrate thickness and the recording density of DVDs and CDs, it is difficult to meet both focusing criterions by a single objective lens. According to the DVD standard, a 0.6-NA objective lens is used to read 0.4 μm shortest pit length and 0.74 μm track pitch. Lenses with large NA, however, are sensitive to coma aberration caused by disk tilt as following:

$$W_{\beta} = \frac{1}{2} NA^3 \beta \frac{t}{n}\left(1 - \frac{1}{n^2}\right) \qquad (1\text{-}2)$$

Where β is the tilt angle, t and n are the thickness and refractive index of the disk substrate, respectively. Therefore, a thin substrate t of 0.6-mm-thick is adopted used in DVDs, which is half of that of existing CDs. However, spherical aberration (SA) occurs when reading a 1.2-mm-thick CD using an objective lens with 0.6 NA designed for reading DVD. The amount of wavefront spherical aberration Ws, written as a power series of the NA and normalized with respective to working wavelength (λ = 635 nm) is given by:

$$W_S = \frac{d}{\lambda}\left\{\left(\frac{n^2-1}{8n^3}\right)NA^4 + \left(\frac{n^4-1}{16n^5}\right)NA^6 + \left(\frac{5(n^6-1)}{128n^7}\right)NA^8 + ...\right\} \qquad (1\text{-}3)$$

where d = 600 μm is the thickness difference between CD and DVD, n = 1.586

(refractive index of polycarbonate) and NA = 0.6 used for DVD system. The first three factors in the power series of NA amounts to 5.81, 1.46 and 0.37 in units of wavelength. These values are too large for achieving diffraction-limited in CD readout.

The easiest way to achieve compatible reading is to use two pickup head module (λ = 780 nm, NA = 0.45 for CDs and λ = 635 nm, NA = 0.6 for DVDs). However, such head design has disadvantages in terms of size and cost. Two methods have been proposed to deal with CD/DVD compatibility issues. One was using a laser diode (LD λ = 635 nm) and two objective lenses, one for DVDs and one for CDs [1-5]. In a CD system, the wavelength is 780 nm and NA = 0.45. When the wavelength 635 nm LD is adopted, a reduced 0.35 NA is sufficient for CD readout. The other method was to use a dual focusing objective lens integrated with a holographic optical component (HOE) on its aspherical surface, as shown in Fig. 1.2.6. In this approach, only the zero- and first-order diffracted light beams are used for DVD and CD, respectively [1-6].

Objective lens for optical pickup is designed to compensate for spherical aberration and sine condition. In order to satisfy the performance requirements with an objective lens, aspherical surfaces on both sides are necessary. However, variable parameters of a single lens design are extremely limited. Therefore, several additional functions of a single lens including HOEs, two objective lenses and liquid crystal shutter [1-7] are proposed for realization of CD/DVD compatibility.

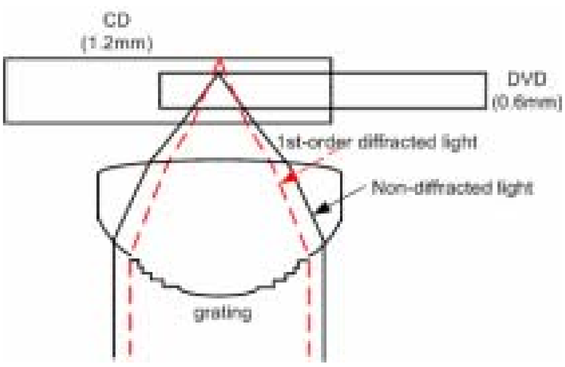


Fig. 1.2.6. Schematic configuration of the dual focus objective lens.

1.2.7 Automatic Focusing

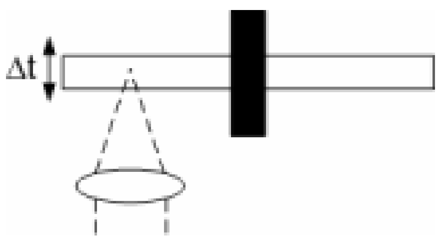
During all read/write/erase operations, two major areas of concern are following the track in the radial direction and keeping the spot in focus. In practice, however, the axial and radial runout of optical disks are two to three orders of magnitude higher than the allowable focusing/tracking errors. Typical values of the relationship between the focused spot and runout are presented in Table 1-I. Therefore, the objective mounted on a small actuator (usually a voice coil) must be controlled to follow these movements in real time. The frequency responses of these feedback systems (also referred to as servo system) are used with a bandwidth of several kHz.

Table 1-I. Typical value of axial and radial runout of the disk systems.

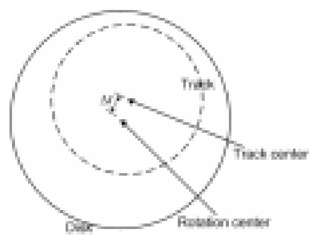
Combined axial runout (Δt)*: 50-200 μm (~100X depth of focus)
Reasons: 1. Substrate thickness variation 2. Disk tilt 3. Spindle wobbles 4. Substrate birefringence
Combined axial runout (Δr): 30-100 μm (~100X focused spot size)
Reasons: 1. Decentration of the tracks of a disk 2. Spindle wobbles 3. Substrate birefringence

The focus sensor in an optical pickup must detect disk defocus with a very high resolution in terms of detector photocurrent (mA/ μm) with sufficiently low noise (<10^{-3} μm-rms) for servo electronics. Various methods have been proposed for deriving a focus error signal (FES) in the opto-mechanical system, as best they can, while minimizing complexity.

* Definitions of axial and radial runout of optical disks:



Axial runout



Radial runout

The Foucault knife-edge sensor, sometimes referred to as the dual half aperture focus sensor, is used to measure the variation of beam cross section as a function of defocus, as indicated in Fig. 1.2.7. The effective acquisition range, which is defined as the maximum deviation range through which the FES is well above the noise, is approximately 30-50 μm in typical value.

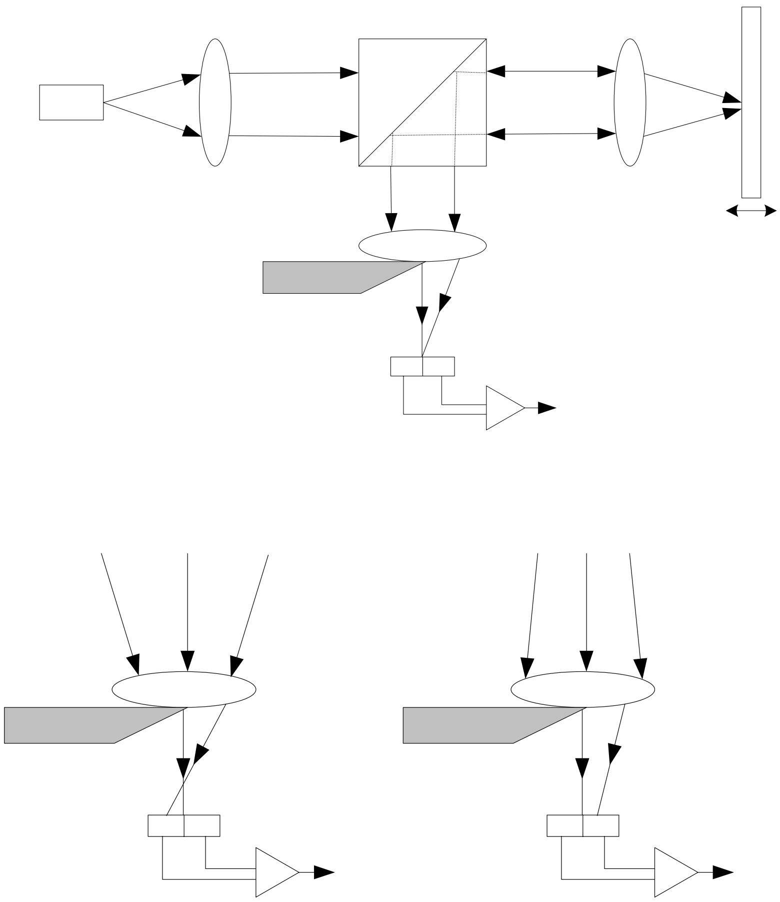


Fig. 1.2.7. Focus error detection by the Foucault knife-edge method. (a) The disk is in focus, and the two halves of the split detector receive equal amounts of reflected light. When the disk is too far from the focus plane (b) or too close to it (c), the balance of detector signals shift to one side or the other.

The astigmatic focus sensor is another focus error detection, which was adopted in the early video disk players by Philips in the 1970's. This approach now is currently used in many CD players and MO drivers. Depending on the convergent angle of the reflected beam, astigmatism is introduced that generates two focal lines along the optical axis in sagittal and tangential planes, as shown in Fig. 1.2.8. Meanwhile, the push-pull tracking signals are also available in the far field of the beam and can be detected by the same quadrant detector. Although it has lower sensitivity and a high level of focus-to-tracking optical crosstalk, its acquisition range can be larger than that of the Foucault knife-edge method.

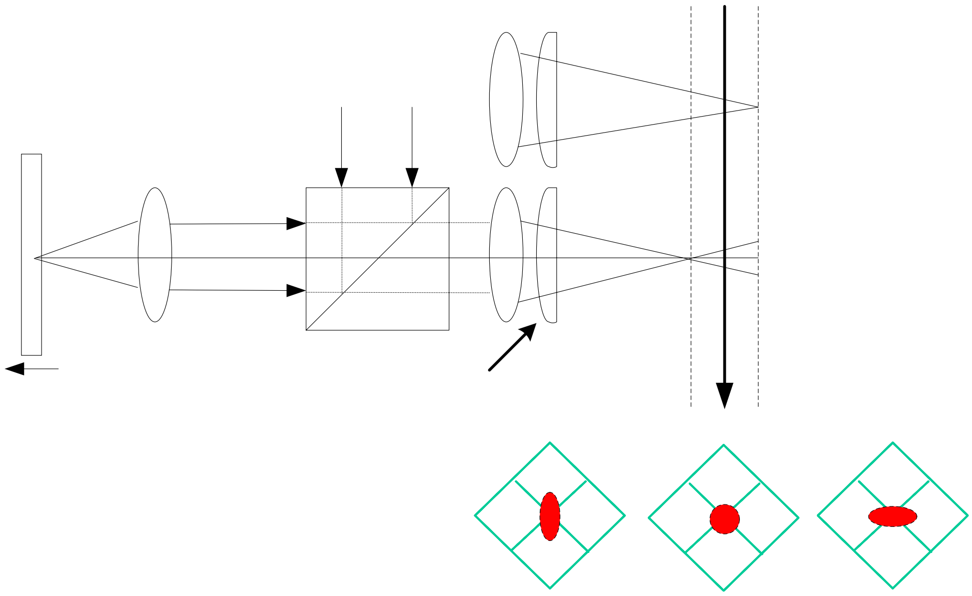


Fig. 1.2.8. Astigmatic focus error detection method.

There are many other schemes for detecting FES, some of which are critical angle prism, spot size detection, and wax-wane. One optical issue with all focus servos is to reduce tracking-to-focusing optical crosstalk, which can be overcome to a high degree by using a differential arrangement of focus detector and hold focus errors to less than 0.2 μm.

1.2.8 Automatic Track-Following

The track error signal (TES) is derived in most pickups from a balanced far field pattern diffracted symmetrically from the two edges of the track. As soon as the spot moves away from the track center, the symmetry breaks down and the light distribution in the far field tends to shift to one side or the other. A split photodetector placed in the path of the reflected light can therefore sense the relative position of the spot and provide the appropriate feedback signal, as shown in Fig. 1.2.9.

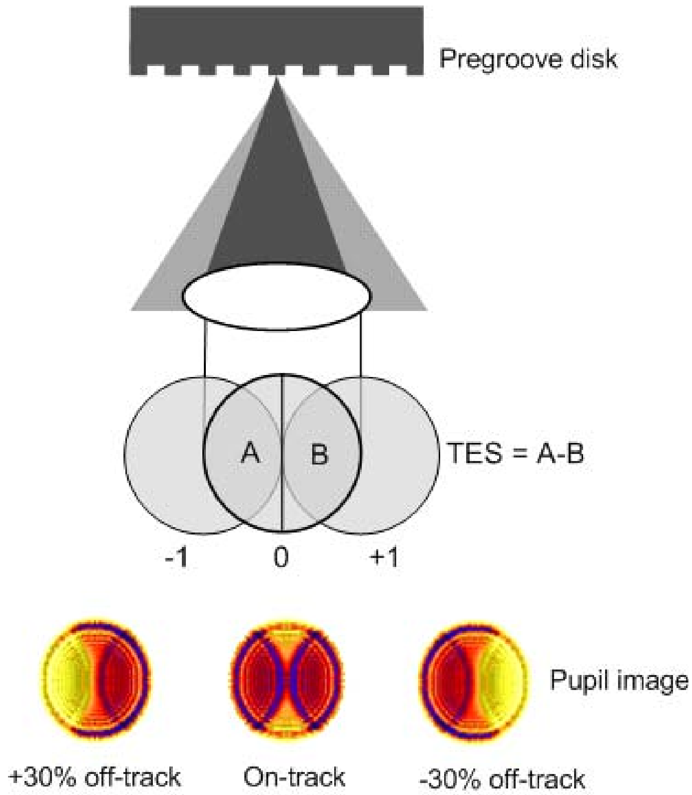


Fig. 1.2.9. The reflected zero-order and the diffracted light that interferes to yield the push-pull track error signal.

Since dynamic track runout is a slow and gradual process, there is actually no need for continuous tracking as done on a groove media. Therefore, a pair of embedded offset-track marks can be used to provide the necessary information for correcting the relative position of the focused spot, as shown in Fig. 1.2.10; this is the essence of the sampled servo method. In this approach, the reflected intensity will indicate the positions of the two servo marks as two successive short pulses. If the beam is on the track center, the two pulses will have equal magnitudes. On the other hand, if the beam is off-track, one of the pulses will stronger than the other one to provide the TES for correction.

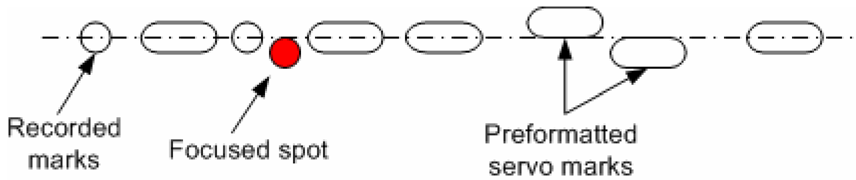


Fig. 1.2.10. In sampled servo tracking, a pair of preformatted marks helps locate the focused spot relative to the track center.

In practice, mechanism for extracting TES from the reflected beam depends on the disk format. Tracking error sensing is usually achieved with either: push-pull (for continuous tracking), sampled-servo (for discrete tracking), or the combination of these methods [1-8, 1-9]. There are other ways for detecting TES such as three-spot, differential push-pull, and differential phase detection. All schemes, when combined with appropriate closed-loop servos, can hold tracking errors to less than 0.01 μm to reduce crosstalk [1-10].

1.2.9 Multilayer Optical Disks

Magnetic drive manufacturers generally use a stack of several magnetic disks to achieve the desired storage capacity within the small volume of a hard drive. The small size and the low cost of magnetic heads allows them to use separate heads for each disk surface without compromising the overall size and price of the drive. In contrast, optical heads are expensive and rather bulky. To achieve volumetric data storage with optical disks, designers have sought methods that rely on a single head for accessing multiple platters. In 1994 IBM researchers demonstrated a system that could read through a stack of six CD surfaces using a single optical head [1-11]. Their system was very similar to a conventional CD player, except that they had taken special care to correct the spherical aberrations when the beam of light is focused through a substrate at different depths. The IBM stack consisted of three thin glass disks (thickness = 300 um) on both surfaces of which the data pits had been embossed. Unlike standard CDs, these disks were not metallized because the focused laser beam had to pass through several such layers before reaching the desired surface. A bare glass surface reflects about 4% of the incident light, and this was apparently sufficient to enable the detection system to retrieve the data and to play back, with high fidelity, the recorded audio and video signals.

Technically, the method described above is straightforward and requires only that the objective lens be corrected for focusing through different thicknesses of the substrate. The separation between adjacent surfaces must be large enough to reduce crosstalk from the data marks recorded on neighboring surfaces. With a 0.6 NA objective lens, a separation of 40 or 50 um is typically enough to assure acceptable levels of cross-talk from these other surfaces.

In the case of writable media, recording and readout of information on multiple platters is more difficult, primarily because storage layers absorb a significant amount of the laser light. Recently dual layer phase-change disks have been proposed and demonstrated in several industrial laboratories. Again, the separation between recording layers was kept at about 40 um to reduce crosstalk, and the laser beam was strong enough to write on the second layer even after half of its power has been absorbed by the first layer. Since focusing through an additional 40 um of spacer layer is within the range of aberration tolerance of typical objective lenses, correction for spherical aberration has not been necessary in these dual layer systems.

1.3 Motivation and Objective of this Dissertation

There are three directions for the innovation of future optical data storage. First, the smaller recording marks are being addressed via high-resolution head technology such as short wavelength blue laser, solid immersion lenses (SILs), higher numerical aperture lenses, and near-field aperture. In addition, a number of novel multilayer media have been designed to provide high-resolution signal enhancements (magnetically induced super-resolution (MSR) [1-12], magnetic amplifying MO system (MAMMOS) [1-13], DWDD [1-14], Super-RENS [1-15], etc.) The material of these techniques include dye-polymer (write-once), phase-change and magneto-optical (rewritable). These techniques have been developed to extend recording density into the range of 10 Gbits/in^2 with 640-660 nm lasers used today. The second direction is the storage of more bits in a given recording mark such as multilevel technology. The third approach is to develop three dimensional recording techniques. Multilayer disks and multiple 2D patterns in a solid storage medium as $LiNbO_3$ are being studied for optical storage applications.

Several approaches to volumetric optical storage, including the extension of present disk systems based on PC and MO media to a layered format, are being actively investigated in the mid of 1990s. Besides, some systems recorded by two-photon absorption and read by fluorescence and volume holographic storage, where data are recorded in a distributed fashion in the volume. In addition, more futuristic approaches are being investigated to utilize the wavelength as the third dimension. Volumetric optical storage is a natural extension of present optical disk systems with a potential to increase the media capacity without significantly affecting the cost of the drives.

Multilayer recording extends the effective areal recording density and capacity per disk. It therefore enables the penetration of new markets with technologies in hand and eliminates pickup head duplication. Since a larger amount of data can be accessed by current pickup head. Furthermore, when the number of layers can be increased, the approach can relax constraints in other dimensions, providing significant cost saving. For example, for larger effective areal density, a multilayer disk system may use larger spot size and use low cost, lower numerical aperture optics and servo systems. However, there are also limitations to the third dimension. These include higher optical power requirements depending on the transparency of the material, dealing with aberrations and interlayer crosstalk while imaging through the volume, extra costs associated with focusing and tracking in three dimensions, and smaller signal levels requiring more complex signal processing and error correction schemes.

The goal of thesis is to increase the recording by using volumetric optical storage. In the study, an “optical switching structure” is designed to increase the recording layers and reduce the interlayer crosstalk in the volumetric disks. The feasibilities of optical switching layer both in rewritable or write-once media are studied, and demonstrated.

1.4 Outline of dissertation

The dissertation is organized as following: The background of volumetric optical data storage technology and optical switching structure for the recording layers in the multilayer disk are presented in Chapter 2. Chapter 3 presents calculated optical properties of the recording layers with optical switching structure. Furthermore, the candidate materials for the optical switching layer are discussed. In Chapter 4, the thermal activated optical switching layer in rewritable multilayer disk is proposed and demonstrated. In Chapter 5, write-once volumetric optical disks using transparent recording material with an optical switching layer is presented and demonstrate experimentally. In addition, fabrication processes and dynamics tests of such recording media are presented in Chapter 6. Finally, discussions, summaries of the dissertation, and recommendations for the future work are given in Chapter 7.

CHAPTER 2

BACKGROUND

Volumetric optical data storage technologies are attractive because they provide higher data capacity than surface storage technologies. In this chapter, three types of the volumetric optical data storage technologies including bit-serial storage, fluorescent multilayer disk, and holographic data storage were presented. Moreover, the advantages of optical switching structure for the volumetric optical disk were discussed.

2.1 Introduction of Volumetric Storage

The decreasing cost of storing data and the increasing storage capacities of ever smaller devices are key issues of optical storage. Current storage needs are being met because improvements in conventional technologies, such as magnetic hard disk drives, optical disks, and semiconductor memories, have been able to keep pace with the demand for greater and faster storage. In optical storages, surface storage technologies are approaching fundamental limits that may be difficult to overcome, such as smaller bits become less thermally stable and harder to access. An approach for next generation data storage is to store information throughout the three dimensional volumetric storage. By storing data within the volume of the recording medium, it is possible to achieve far greater storage densities than current technologies offer.

The main difference between surface and volumetric optical storage is the storage media. In surface optical storage, the focused laser beam illuminates only the data layer being accessed; in volumetric storage, the focused laser beam partially illuminates unrelated data layer. In the recording process, the volumetric readout process must retrieve only the desired data bits, with tolerable amounts of crosstalk. Then, data was reproduced by channel electronics from the signal detected by the detector.

Storage capacity of the volumetric storage media depends on the volumetric density and the number of user bits per data layer. Recording rate depends on how long it takes to selectively address the desired data layer, and the dwell (lasing delay [2-1]) time of the laser required to store the data. Likewise, readout rate and latency (the delay to a random data stream) depend on the speed of selective addressing, and the dwell time of the laser required retrieving the data. For example, if the storage media is physically moved to selectively address, this often tends to dominate the readout rate and latency. But if the storage media is a continuously spinning disk, the latency can significantly exceed. Next, three kinds of volumetric storage media were introduced as examples in the following paragraph.

2.1.1 Bit-Serial Storage

The most straightforward version of volumetric optical storage is the extension from surface optical storage: data bits stored not only on the surface but throughout the volume. Besides, the selective addressing of data layers is done by focusing the laser beam. Such multiple layers storage approach was done without changing much of the readout hardware [2-2]. The focus servo becomes responsible for changing between layers of different depth, in addition to its primary task of locking onto a layer once one is chosen. Crosstalk from other layers (the possibility of confusion for the focus servo) is minimized by separating data layers a fairly large distance as shown in Fig. 2.1.1 (this spacing is ~ 55 um for DVD-ROM [2-3]). The adequate spacing layer ensures that when the converging beam passes through the nearest neighboring layers, the large spot size covers enough data bits that the loss in transmission due to reflecting pits (and the out-of-focus crosstalk signal in reflection) remains roughly constant [2-4]. If the layers are moved closer together, more crosstalk reaches the detector, and the smaller pool of illuminated data bits means that the statistical variation of random ON and OFF bits can become a significant noise source.

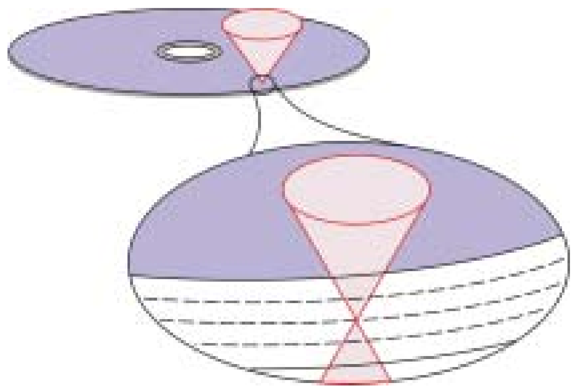


Fig. 2.1.1. A pre-fabricated disk with multiple layers is accessed from one surface for volumetric optical storage.

As more layers are added, then the reflectance and transmission of each layer needs to be adjusted so that the signals from each layer are equally detectable. In the DVD-ROM, for example, this is done by using a gold coating on the upper layer and aluminum on the bottom [2-5]. The signal-to-noise ratio is reduced not only by the lower average signal level, but by the scattering of the reflected beam as it passes through the data layers on its way back to the detector. As the number of layers increases and the bottom layers move relatively deep into the substrate, a tradeoff emerges between high numerical aperture and the working distance between the lens and disk surface.

Spherical aberration, usually corrected by reading/recording optics, now varies from layer to layer. Without adaptive correction for each layer, this rapidly limits the number of accessible layers. Since only one layer can be exactly corrected for (probably in the middle of the disk), the spot-size is maximum at either the upper or bottom layers [2-6]. Birefringence of the substrate should also become more problematic as the optical path lengths inside the material increase.

An additional and important consideration to extend a next-generation-DVD standard beyond two layers is the difficulty in fabricating prerecorded disks with more than two data layers. Currently, while DVD disks can contain as many as four layers, only two layers are read from any surface (i.e., the four-layer disk must be flipped over in a standard one head drive). Therefore, in fabrication, each half of the disk is fabricated with injection molding and is then glued to another half to produce the final disk. If a second data layer is needed on either half, then a 55 um (±15 um) thick layer of ultraviolet (UV) curable polymer is laid down and the bottom layer stamped into this layer [2-7]. Apparently, one of the main issues is gluing the substrates together without warping the resulting disk, since commercial DVD drives do not contain a tilt servo to compensate for warped disks [2-2]. However, other challenges such as registering the layers so that the pickup head that is tracking on one layer can move to another and still know which track it will be on, and keeping the layer thicknesses uniform so that the focus servo can always distinguish between layers are needed to overcome.

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2.1.2 Fluorescent multilayer disks

Other bit-serial methods are variations upon the basic idea of an extended DVD, usually solving one of its basic problems but unavoidably introducing others. For instance, one of the problems with an extended DVD is that the return signal is perturbed by data layers on the light path. Such drawback can be avoided by using fluorescent readout, a technique promoted for layered disks [2-8, 2-9]. The readout light is then incoherent and can be wavelength-shifted away from the incoming laser beam so that a filter can block scatter and crosstalk at the laser wavelength from reaching the detector. Of course, this fluorescent dye needs to have the same index of refraction as the substrate, both to avoid the same perturbation of the return signal and to prevent strong reflection of the readout laser. Two-photon fluorescence multilayer (i.e., two-photon absorption followed by fluorescence) was first adopted in fluorescent multilayer disk [2-10, 2-11] technology. Since the fluorescence signal follows the square of the light intensity, the output signal is only efficiently generated where the readout laser beam is focused and provided the layer discrimination.

While the fluorescent multilayer disk removes some of the difficulties in extending localized bit storage to multiple layers, it retains several issues, such as the layered disk must be fabricated carefully with an additional dye-filling step in which all pits are filled with dye. Assumably to ensure equal filling of all pits, a thin continuous layer of dye exists between pits, which creates a background fluorescence signal [2-12]. After disk fabrication, the desired data are then recorded in these pits with a recording laser, either thermally by destroying the initial fluorescence, or by driving a photochemical reaction which makes the dye in that pit fluorescence.

Whether this writing process is bit-serial or bit-parallel, the economy of disk fabrication will likely be significantly different from that of CDs and DVDs. The recording speed will depend strongly on how much writing power is needed. All scientific literature on 2-photon fluorescence has involved high-power lasers, typically ultrashort pulsed lasers capable of high intensities [2-13~16]. Another issue is the readout speed, since the fluorescent dye produces a signal of 1 uW [2-12], much lower than the signal from conventional DVD disks (3-5mW read laser and >50% and >20% reflectivity for DVD-ROM and DVD-RAM, respectively [2-3, 2-7]). These lower signal levels in turn require reduced rotation speed. While aggregate readout rate can be regained by using parallel readout of multiple tracks from the same layer onto a CCD camera [2-10], this lower rotation rate will still lead to a longer latency than DVD (already one of conventional optical storage's weak points).

Other methods proposed for improving layered bit-serial localized volumetric optical storage have included the use of optical coherence domain reflectometry (using partially coherent light to get depth discrimination for very weakly reflecting layers), and the use of transparent disks in which abrupt, local changes in layer thickness are detected by measuring the optical path difference between two slightly offset focused beams*.

* Differential interference contrast microscopy.

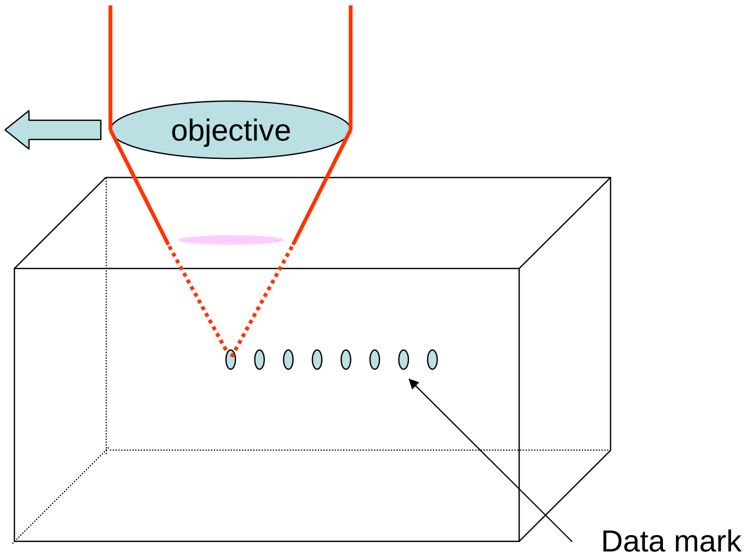


Fig. 2.1.2. Bits are localized within an initially homogeneous block of media by careful focusing and either confocal imaging, nonlinear material response, or both.

2.1.3 Holographic Data Storage

In contrast to localized-bit recording, where each bit of data is assigned to a particular location within the storage volume, holographic storage distributes data throughout a volume in a delocalized way. A hologram is a recording of the optical interference pattern that forms at the intersection of two coherent optical beams. The object beam carries the information to be stored, while the reference beam is designed to simply reproduce at a later stage, as shown in Fig. 2.1.3 (a).

To record a hologram, the reference and object beams are made to overlap in a photosensitive medium, such as a photopolymer [2-17] or inorganic crystal [2-18] or even photographic film [2-19], where the resulted optical interference pattern creates chemical and/or physical changes. As a result, a replica of the interference pattern is stored as a change in absorption, refractive index or thickness. Since the pattern contains information about both the amplitude and the phase of the two light beams, when the recording is illuminated by the readout beam, some of the light is diffracted to “reconstruct” a weak copy of the object beam, as shown in Fig. 2.1.3 (b). If the object beam originally came from a 3-D object, then the reconstructed hologram makes the 3-D object to reappear. Besides, the hologram can also be read out by illuminating it with a counter-propagating reference beam, which reconstructs a phase-conjugate copy of the original object beam. This beam returns to its original point, where the bit value can be read without requiring a high-quality imaging system, as illustrated in Fig. 2.1.3 (c). A third way to retrieve data involves illuminating it with a diverging object beam, which reconstructs the original plane wave reference beam. This beam is focused onto a detector and provided an optical measurement of the correlation between the stored data and the illuminating object beam, as illustrated in Fig. 2.1.3 (d).

In holographic storage, data sets are transferred to and from the storage material as 2-D images composed of thousands of pixels, with each pixel representing a single bit of information. However, no one location in the crystal is responsible for storing that one bit; each bit is distributed throughout the recorded interference fringes. Since an entire “page of data” can be retrieved by a photodetector at the same time, rather than bit-by-bit, the holographic scheme promises fast readout rates as well as high density. If a thousand holograms, each containing a million pixels, could be retrieved every second, for instance, then the output data rate would reach 1 Gigabit per second. Despite this attractive potential and fairly impressive early progress [2-20], however, research into holographic data storage all but died out in the mid-1970s mostly because of the lack of suitable devices for the input and output of pixelated 2-D data pages.

In the early 1990s, interest in volume-holographic data storage was rekindled [2-21] by the availability of devices that could display and detect 2-D pages, including charge coupled devices (CCD), complementary metal-oxide semiconductor (CMOS) detector chips and small liquid-crystal panels. The wide availability of these devices was made possible by the commercial success of hand-held camcorders, digital cameras, and video projectors. With these components in hand, holographic-storage researchers have begun to demonstrate the potential of this technology in the laboratories [2-22, 2-23].

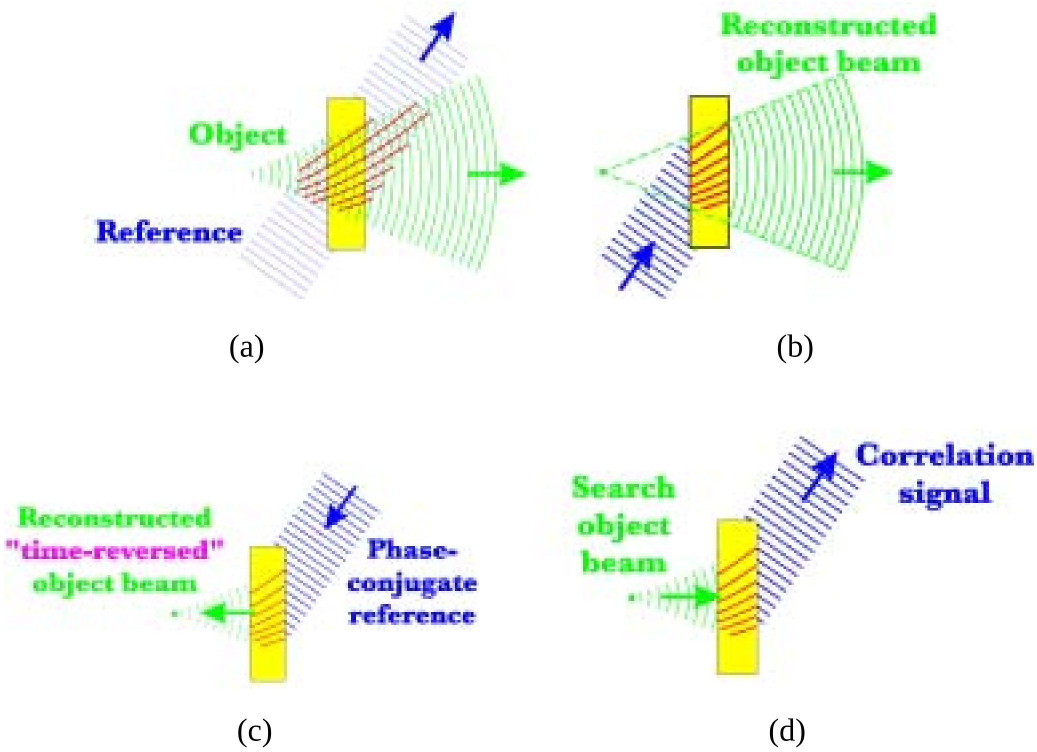


Fig. 2.1.3. Schematics diagram of recording and reading data using holograms. (a) Holographic storage of a single data bit. (b) The hologram is read out using the original reference beam, diffracted by the stored interference pattern to reconstruct the original spherical wavefront. (c) The hologram is read out by illuminating it with a

counter-propagating reference beam. (d) A third way to retrieve data involves illuminating it with a diverging object beam.

To use volume holography as a storage technology, digital data must be imprinted onto the object beam for recording and then retrieved from the reconstructed object beam during readout. The device for putting data into the system is called a spatial light modulator (SLM), a planar array consisting of thousands of pixels. Each pixel is an independent microscopic shutter that can either block or pass light using liquid-crystal or micro-mirror technology. Liquid crystal panels and micro-mirror arrays with 1280 × 1024 elements are commercially available due to the success of computer-driven projection displays. The pixels in both types of devices can be refreshed over 1000 times per second, allowing the holographic storage system to reach an input data rate of 1 Gbit per second-assuming that the laser power and material sensitivities permit.

The data are read using an array of detector pixels, such as a CCD camera or CMOS sensor array. The object beam often passes through a set of lenses that image the SLM pixel pattern onto the output pixel array, as shown in Fig. 2.1.4. To maximize the storage density, the hologram is usually recorded where the object beam is tightly focused. When the hologram is reconstructed by the reference beam, a weak copy of the original object beam continues along the imaging path to the camera, where the optical output can be detected and converted into digital data.

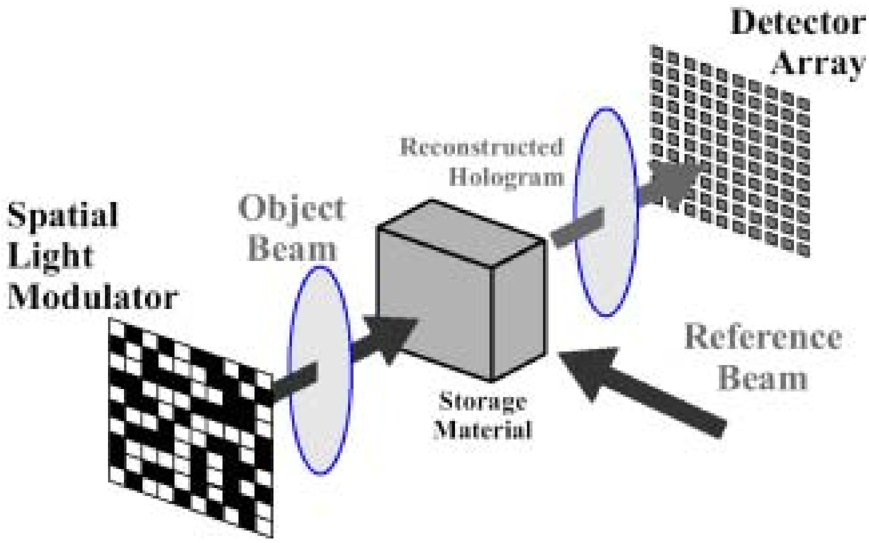


Fig. 2.1.4. Data are imprinted onto the object beam by shining the light through a pixelated input device called a spatial light modulator. A pair of lenses image the data through the storage material onto a pixelated detector array, such as a CCD. A reference beam intersects the object beam in the storage material, allowing the holograms to be stored and retrieved later.

2.2 DVD Compatible Multilayer Disk

2.2.1 Overview of Multilayer DVD disk

In 1993, Rosen, et al. developed a volumetric disk with six read-only layers. Due to the difficulty of stacking so many layers in an optical disk, the disk was not put into practice [2-24]. Three years later, Rubin, et al. devised two kinds of dual-layer write-once optical disks by applying special phase change and dye materials [2-25, 2-26]. To make the lower recording layer optically accessible, one very thin top phase change layer was employed in the dual layer structure. One special interference film was added in contact with the top layer to increase its reflectivity and thus to maintain its readout and servo performance. Unlike usual reversible phase change media, the write-once read-many (WORM) phase change material utilized in the design recorded crystallized data pits on unrecorded amorphous data surface. In the other design of dual layer WORM optical disk, a similar dual layer structure with an air-gap, and a specially designed dye material, somewhat similar to the used in CD-R, was employed. In 1997, Nishiuchi, et al. proposed a dual layer write once structure using Te-O-Pd phase change material [2-27]. This new structure provided better recording/readout characteristics, while the relatively poor stability limited its applications.

To further extend the application of current optical disks in single usage of read-only, write-once, or erasable function, media with different recording functions can be implemented on data layers of a multi-functional optical disk, as shown in Fig. 2.2.1. Till now, still few documents reported optical disks with multi-functionality due to the immaturity of volumetric optical storage.

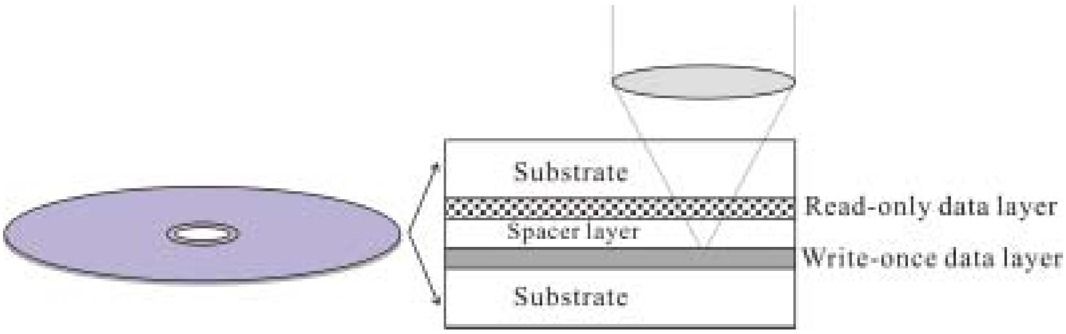


Fig. 2.2.1. A multilayer optical disk with read-only and write-once functions.

Similar to CD, dual-layered DVD measures 12 cm in diameter and 1.2 mm in thickness, while the data are recorded on one or two data layers face-to-face bonded 0.6 mm substrates [2-28], as shown in Fig. 2.2.2. The beam may be incident from different disk sides to access the data layers of a double-layered DVD; in contrast, the laser beam can transmit through a semi-reflective layer to access the deeper layer of a dual-layered DVD. Due to the interlayer crosstalk [2-29], the disk capacity of a dual-layered DVD (for example, DVD-9 of 8.5 GB/disk) is of less than that of a double-layered DVD (for instance, DVD-10 of 9.4 GB/disk).

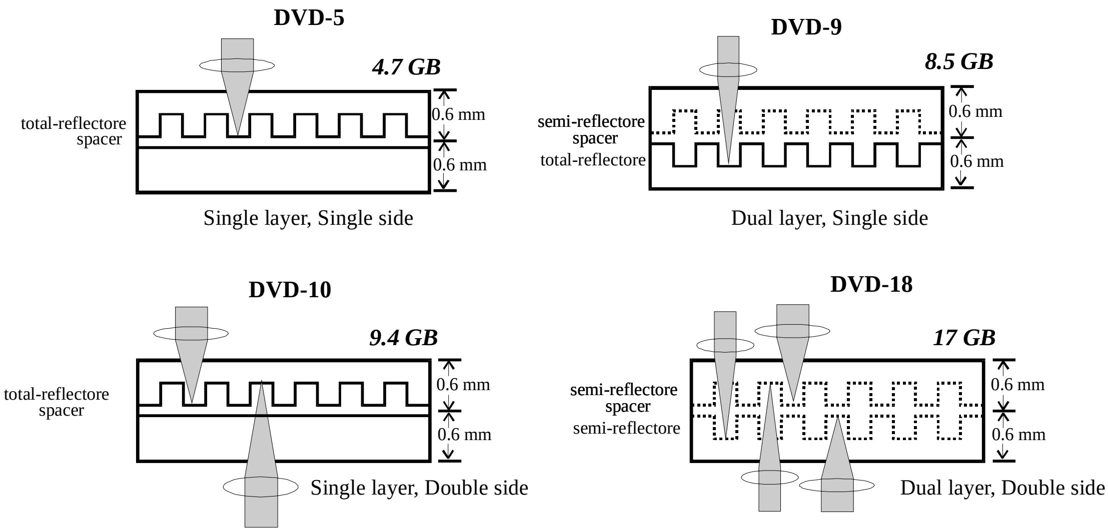


Fig. 2.2.2. Four kinds of read-only DVD disks: DVD-5 of 4.7 GB, DVD-9 of 8.5 GB, DVD-10 of 9.4 GB, and DVD-18 of 17 GB.

2.2.2 Principles of Multilayer DVD Optical Storage

Volumetric optical storage increases recording density by employing multiple data layers as recording media. Two adjacent layers of a volumetric optical disk are separated by interlayer spacer to isolate the data layers and to suppress the interference induced between the data layers. The thickness of interlayer spacer should essentially be greater than the depth of focus of the beam, so that the data recorded on the out-of-focus layers shall not be destroyed or modified by the intense optical energy distributed within the depth-of-focus, as shown in Fig. 2.2.3. A dual layer optical disk, composed by only two data layers, is a volumetric optical disk of the simplest in structure. The top data layer of a dual layer optical disk is designed to be semi-reflective so that the lower total-reflective one is optically accessible, as shown in Fig. 2.2.4.

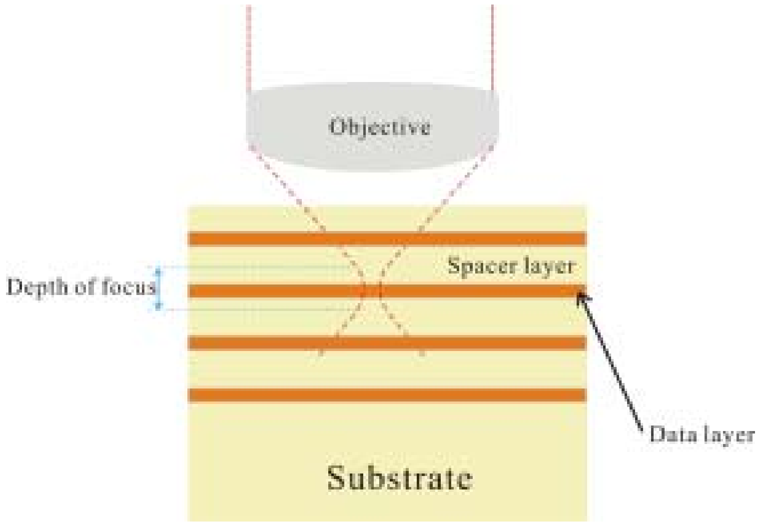


Fig. 2.2.3. Depth of focus of a focusing laser beam.

In reading a volumetric optical disk, interlayer crosstalk is induced due to the presence of out-of-focus layers. In readout, the out-of-focus layers shall reflect back part of the laser energy, which interferes the desired readout signal and degrades the readout performance, as shown in Fig. 2.2.5. Thus, it is essential to reduce the effect of interlayer crosstalk in designing a volumetric optical disk system. Through optimization of disk structure, readout optics and electronics, interlayer crosstalk can be adequately suppressed, and effective write/readout on data layers if a multilayer optical disk can be achieved by applying reasonable power of optical irradiation.

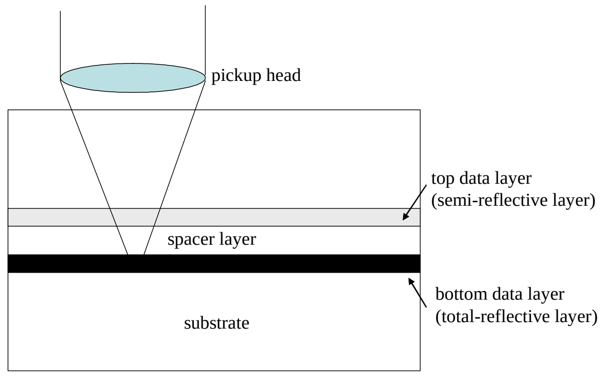


Fig. 2.2.4. A dual layer disk is composed of a semi-reflective and a total-reflective data layer.

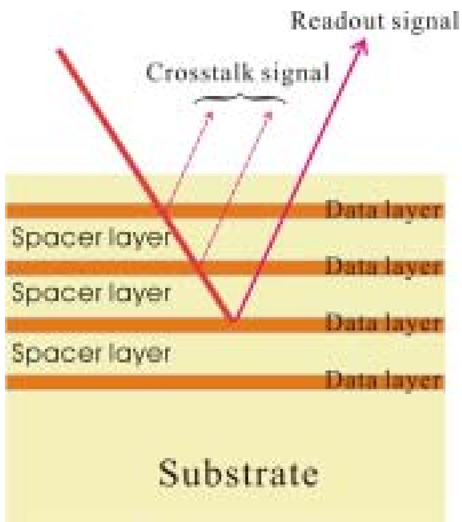


Fig. 2.2.5. Interlayer crosstalk in a volumetric optical disk.

2.3 Optical Switching Structure in Multilayer Optical Disk

2.3.1 Interlayer Crosstalk in the Dual-layer Optical Disk

The dual layer optical disk, a simplest structure of multilayer optical disk, is comprised of data layers 1 and 2 of high transmittance (T) and high reflectance (R), respectively, where layer 1 is the first data layer impinged by laser beam and layer 2 is the second one. The data layers are separated from each layer by a spacer to reduce the interlayer interference. The RF readout signal and interlayer crosstalk can be derived by the diffraction-limited and enlarged laser spot imaged on the focused and out-of-focus data layers of the dual-layer optical disk, respectively. For a dual-layer optical disk, there are two readout/write-in modes: “mode 1” is defined to read/write the top data layer, and “mode 2” is defined to read/write bottom data layer, as shown in Fig. 2.3.1. In the mode 2, the top data layer falls outside the depth of focus of the optical head and reflects back proton of the readout radiation, which then couples into the readout signal and induces interlayer crosstalk. On the top data layer, the laser light is spread out and results in an enlarged laser spot. It is the laser beam reflected from the enlarged spot that intrudes into the readout channel and induces interlayer crosstalk. Suppose that the FWHM of the diffraction-limited spot was 0.6λ/NA, the 1/e radius of the enlarged spot illuminated on the top data layer was found to be about 20 um using λ = 650nm and NA = 0.6, as illustrated in Fig. 2.3.2.

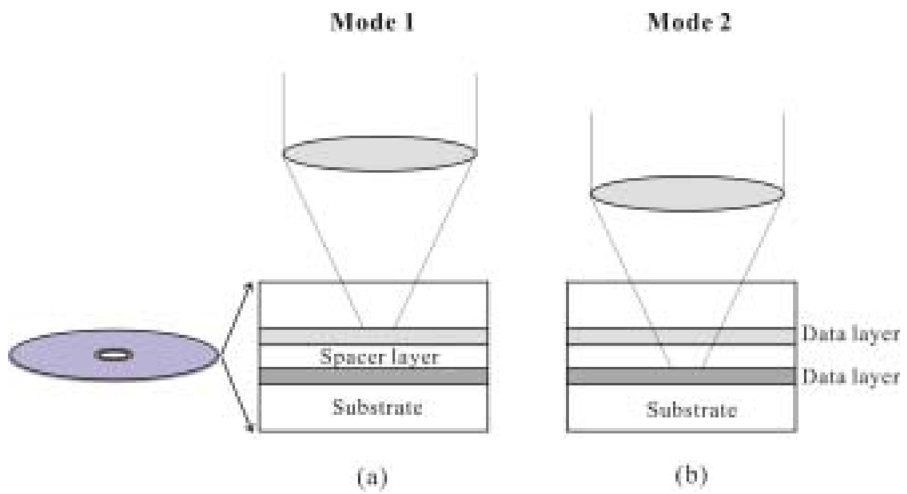


Fig. 2.3.1. When laser beam focus on (a) top data layer or (b) bottom data layer.

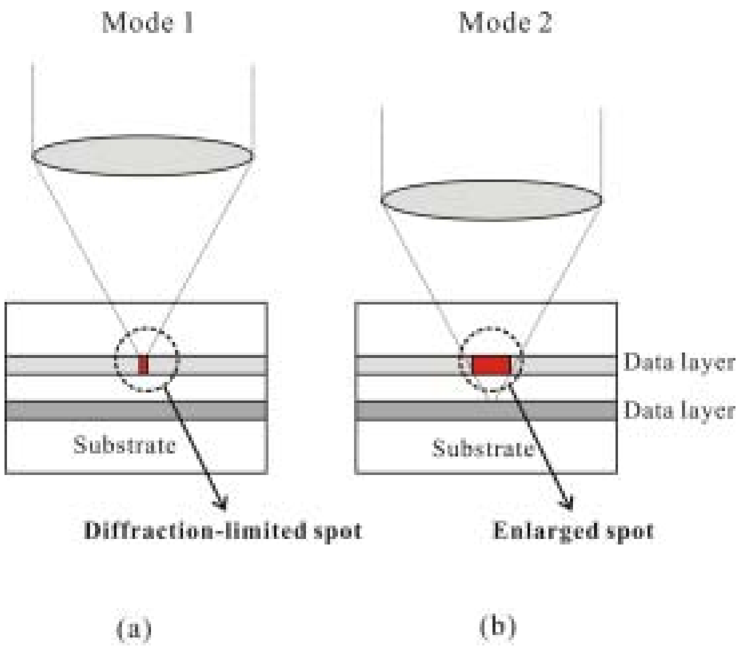


Fig. 2.3.2. The laser spot on the top data layer in modes (a) 1 and (b) 2.

The magnitude of interlayer crosstalk when accessing bottom data layer (mode 2) is chiefly determined by the amount of optical energy allocated onto the top data layer and highly depends on the reflectance (R) of the top data layer. Likewise, the amplitude of readout signal (RF signal) in mode 1 is also proportional to reflectance (R) of the top data layer. The out-of-focus data layer obstructs the incident beam and attenuates the RF readout signal; the intervention of interlayer crosstalk to RF readout signal degrades the readout contract. Furthermore, the laser power needs to be properly increased to compensate for the loss of optical energy in transmitting through the semi-reflective layer for recording signal on the bottom layer of the dual-layer optical disk. Therefore, through adequate configuration of optics characteristics of top data layer is necessary to balance readout signals from both data layers with low interlayer crosstalk.

2.3.2 Optical Switching Structure in the Dual-layer Optical Disk

In a dual-layer optical disk, the optical characteristics (R, T, A) of the top data layer affect the quantity of interlayer crosstalk and peak laser power on the bottom data layer while reading and writing, respectively. Besides, the transmittance of top layer of a dual-layer optical disk must be sufficiently large for accessing another data layer. Therefore, adequate optical characteristics design of top data layer is essential for a dual-layer optical disk. But the rewritable type medium structures, such as phase change disk or magneto-optical disk, exhibiting low transmittance are not easy to design for the rewritable top layer in the dual-layer optical disk. In this dissertation, an optical layer attached to top recording layer is proposed to allow high absorption and high transmittance in top layer in the reading/recording modes 1 and 2, respectively.

A diffraction-limited laser spot is focused on the top data layer in the reading/recording mode 1. Compare to the other mode, higher power intensity (or temperature distribution) falls on this focused region. Thus, a light intensity (or thermally) controlled optical switching structure sandwiched between recording layers, as shown in Fig. 2.3.3, is proposed to allow high absorption and high transmittance in top data layer when the laser beam is focused on top and bottom layers, respectively. More data layer can be realized on a disk substrate by using optical structure in the multilayer optical disk. Further properties of optical switching structure in the disk are discussed in the following chapters.

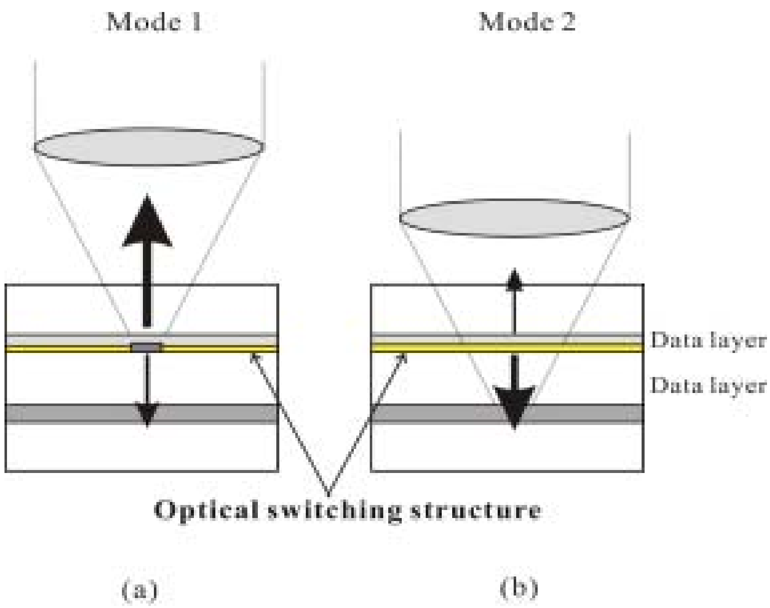


Fig. 2.3.3. Schematic diagrams of optical switching structure modulates the optical characteristics to be high reflectivity and high transmittance top data layer in modes (a) 1 and (b) 2, respectively.

2.4 Summary

Three different volumetric recording methods including bit-serial storage, fluorescent multilayer disk, and holographic data storage were presented in this chapter. Above all, bit-serial type multilayer optical disk has high market potential to become next generation high data capacity media for its DVD compatibility. Besides, an optical switching structure added to recording layers is proposed to modulate the optical characteristics of recording layers by the diffraction limit laser spot to optimize reading/recording processes.

CHAPTER 3

OPTICAL SWITCHING STRUCTURE IN MULTILAYER OPTICAL DISK

Owing to the presence of out-of-focus recording layers in volumetric optical disks, laser energy is decreased in reading/writing the targeted active layer. A non-linear optical material as an optical switch added to recording layers is proposed to modulate the optical characteristics of recording layers by diffraction limit laser spot impinged on it or not. The added optical switching structure can reduce laser energy and to increase recording sensitivity for reading and recording, respectively. Consequently, reading/recording on active layers of volumetric optical disks can be optimized.

3.1 Introduction

The recording capacity of the phase-change optical disks has been increased by adopting high density recoding technologies, such as the mark-edge recording of using multiple laser-pulse trains and the land groove recording. However, to record more information or longer video, a significantly higher recording capacity is required. To realize a drastic increase of the recording capacity, a dual-layer recording method [3-1] aims to double the recording capacity by recording on two active layers from the same side of the disk. This method can realize dual layer DVD-RAM with 8.5GB capacity on one side of optical disk using a conventional pickup of 0.6 NA lens and the laser wavelength of 650 nm.

The dual layer optical disk was comprised of data layers 1 and 2 of high transmittance (T) and high reflectance (R), respectively, where layer 1 is the first data layer impinged by laser beam and layer 2 is the second one. Therefore, low power absorption efficiency and lower reflected signal were obtained while writing and reading respectively on layer 1.

3.2. Optical Switching Layer in the Multilayer Optical Disk

The upper data layer of a dual layer optical disk is designed to be semi-reflective so that the lower total-reflective one is optically accessible. But critical optical characteristics of this semi-reflective are needed to balance the readout signals and recording sensitivity from both recording layer, especially for the rewritable type media such as phase-change type and magneto-optical (MO) type recording materials. Phase-change media, typically of GeSbTe [3-2~3] requires the coexistence of crystalline and amorphous states and distinct optical properties between them. [3-4] Effectuated by different shapes of laser pluses, optical recording/erasure are enabled by phase transformation of phase-change media between these two solid states. [3-5, 3-6] As to MO media, the recording and readout involve reversal of magnetic moments and rotation of Kerr angle, respectively. It is difficult to switch magnetic file with frequency as high as modulated data stream, thus, MO media are commonly erase before writing. With an external field of fixed direction, the recorded MO marks can be erased while they are scanned under the optical stylus

Enjoying readout compatibility with read-only media and capability of one-beam direct-overwrite, phase-change technology is more suitable for application in multilayer optical disks. [3-4, 3-7~8] But low transmittance of metallic-based phase-change materials is still a challenge to achieve phase-change semi-reflective layer on the dual-layer optical disk. Thus, an upper data without metallic reflector for the layer 1 of dual layer optical disk was adopted by Matsushita. [3-9] High writing power for recording upper and bottom layers are required because poor energy absorption of upper layer and shield effect by the upper layer, respectively. In order to overcome the issue, an optical switching structure attached to upper recording layer is proposed to reduce laser energy and to increase recording sensitivity for reading and recording on both recording layers, respectively.

Optical characteristics of upper recording layer with optical switching layer can be modulated by the reading/recording modes. In the reading/recording mode 1, for example, temperature in the focused spot area is higher than other area. The temperature- sensitive optical switching structure is activated and enhances the energy usage efficiency and recording sensitive of upper recording layer while recording. In mode 2, the upper recording layer remains is in high transmittance state so that the interlayer interference is reduced and laser energy onto bottom layer is enhanced.

3.3 Mathematical Modeling

The transmittance of layer 1 of a dual layer optical disk must be sufficiently large. Thus, a structure with no metallic reflector for the layer 1 of dual layer optical disk was adopted by K. Nagata *et al* [3-9]. A sample of 80*nm* ZnS-SiO_2/15*nm* GeTeSb/20*nm* ZnS-SiO_2 disk structure for layer 1 met the condition mentioned above was selected and shown in Fig. 3.3.1 (a) [3-9], whose reflectance/absorption/transmittance (R/A/T), calculated by thin film theory, are

10/45/45% and 21/57/22% in amorphous and crystalline states, respectively.

Thermo-chromatic material [3-10] undergoes a remarkable thermally induced reversible semiconductor-to-metal phase transition, results in significant changes in its optical properties. Above the transition temperature (T_t), the material is metallic and highly reflective; below is dielectric, highly transparent and low absorption. For a dual layer optical disk, by attaching the material with layer 1, as shown in Fig. 1 (b), so that layer 1 behaves as a thermo-induced optical switch. When the laser beam was focused on layer 1, the temperature of layer 1 was increased above T_t to be highly absorptive (*i.e.* optical switch is turn "on"), otherwise, highly transparent (*i.e.* optical switch was turn "off"). To examine optical switching effect, a dual layer optical disk with optical switching layer was modeled.

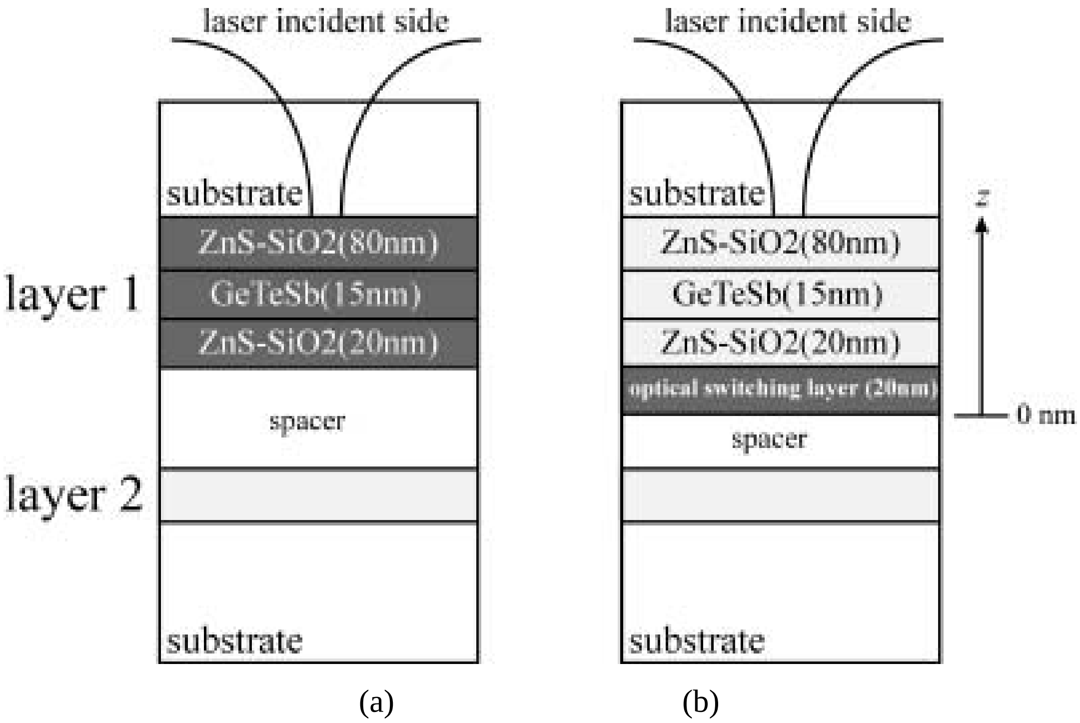


Fig. 3.3.1. Schematic of a dual layer optical disk with (a) no metallic reflector and (b) optical switching layer structure.

3.4 Simulation Result

When laser beam was focused on layer 2 (optical switch is turn “off”), optical characteristics as a function of refractive index (*n*) of optical switching layer of 20 *nm* thick were calculated by thin film theory [3-11]. As illustrated in Fig. 3.4.1, the reflectance and transmittance increase with *n* in amorphous (amo) and crystalline (cry) state of layer 1. The disk with a switching layer of n = 3.0 thus was selected for quantitative analyses, whose R/A/T are 16/28/56% and 26/43/31% in amorphous and crystalline states, respectively. When laser beam was impinged on layer 1 (optical switch was turn “on”), the optical switching layer was metallic, resulted in high extinction coefficient (*k*). R/A/T as a function of *k* for an optical switching layer of *n* = 3.0 was selected and shown in Fig. 3.4.2. Absorption of layer 1 increases rapidly with *k*. R/A/T were 3/70/27% and 17/71/12% in amorphous and crystalline states, respectively, when *k* = 2. The calculated results suggest that laser light can be modulated by the optical switching layer as *k* of thermo-chromatic material in “off” state is almost 0, and *n*, *k* in “on” state are larger than another state.

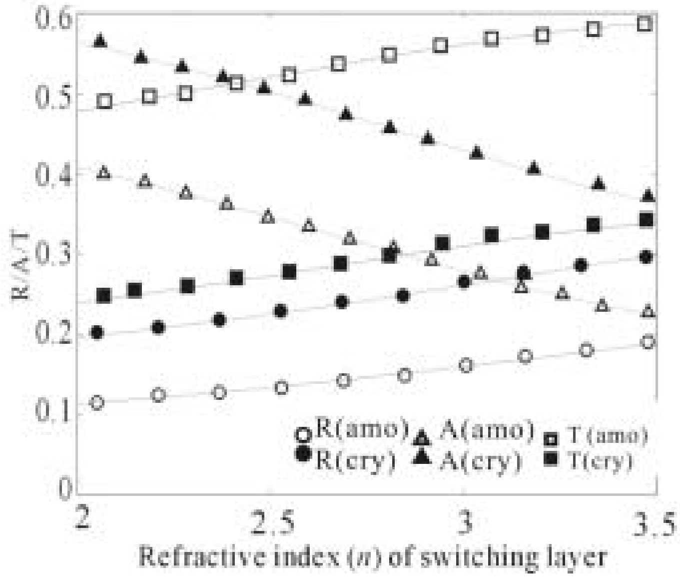


Fig. 3.4.1. R/A/T of layer 1 as a function of refractive index (*n*) of switching layer, as optical switch is in “off” state.

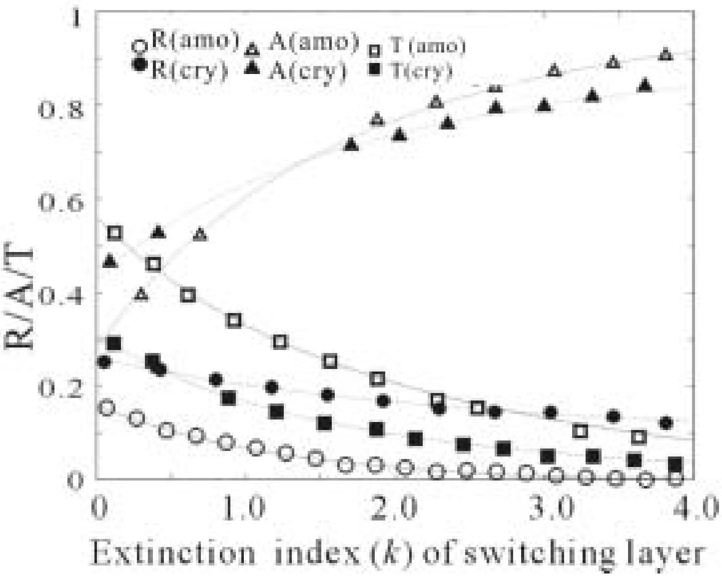


Fig. 3.4.2. R/A/T of layer 1 as a function of extinction coefficient (*k*) of switching layer, as optical switch of layer of n=3.0 is in “on” state.

The state of the optical switching layer was controlled by temperature. To ensure that temperature was high enough to activate the optical switching layer, a Gaussian-distributed diffraction limited spot impinged normally on layer 1 of dual layer optical disk was then analyzed by thermal simulation program "Temprofile" [3-12]. To explore the maximum allowable transition temperature (T_t) of thermo-chromatic material for optical switching layer, temperature difference between an active layer and an optical switching layer during recording was calculated. The thermo-chromatic film (optical switching layer) was metallic as above the transition temperature, with chosen specific heat C = 2 ($J/cm^3\ {}^ok$) and thermo conductivity K = 2 ($J/cm\ sec\ {}^ok$) [3-13]. Briefly, n = 3, k = 2 and C = 2, K = 2 and parameters listed in Table 3-I were adopted to calculate the temperature profile of cross section in layer 1 of dual layer optical disk. As illustrated in Fig. 3.4.3, temperature on the optical switching layer could be raised over transition temperature (T_t) during recording. These calculated results reveal that optical switching layer could change optical characteristics of layer 1. Consequently, a thermo-chromatic material of low transition temperature and high thermo conductivity is applicable for an optical switching layer in dual layer optical disk.

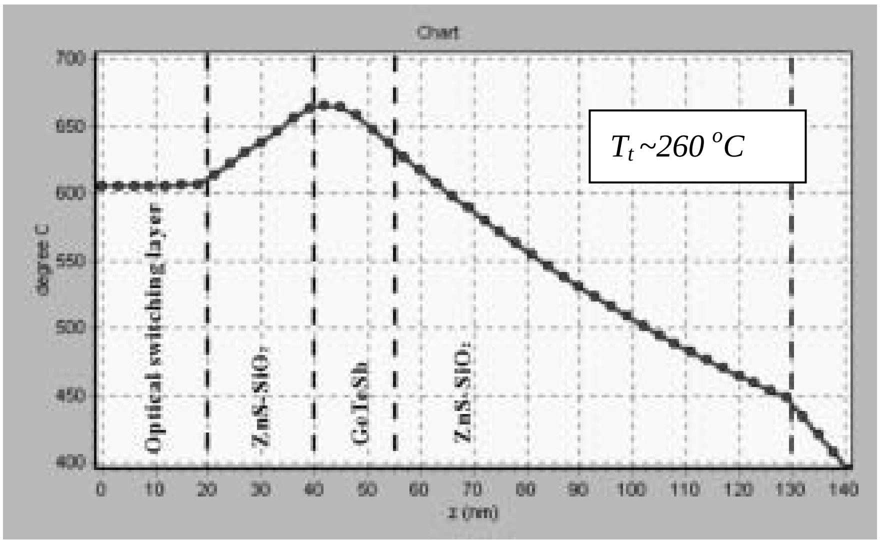


Fig. 3.4.3. Numerical calculated temperature profile for cross section of layer 1 in the dual layer optical disk with optical switching layer, the temperature profile is depicted in the z direction (as shown in Fig. 1) form the bottom of layer 1.

Table 3-I. The optical and thermal parameters of the materials used in the recording analyses.

Disk substrate and thin film layers	Index of refraction n	Extinction coefficient k	Heat capacity C (J/cm^3-ºK)	Thermal conductivity K (J/cm-k-s)
Polycarbonate substrate	1.58	0.00	1.500	0.00223
Al	2.06	7.03	2.454	2.14400
ZnS-SiO2	2.10	0.00	2.055	0.00628
GeTeSb (Crystalline)	5.39	3.18	1.288	0.00580
GeTeSb (Amprphous)	4.53	1.21	1.288	0.00580

3.5 Advantages on Reading and Recording

Compared R/A/T of layer 1 with those of a conventional dual layer optical disk, the simulated results reveal that layer 1 with an additional optical switching layer results in:

For recording on both layers: increase absorption of layer 1 by 30% when laser beam focuses on it. Hence, peak power to record on layer 1 can be reduced. Besides, transmittance of layer 1 is increased by 10% as laser beam focuses on layer 2. Thus the reflectance of layer 2 can be increased and peak power to record on layer 2 can be reduced.

For reading on layer 1: increase the contrast, defined as $(R_{top}-R_{bottom})/2(R_{top}+R_{bottom})$, of reflected beam from layer 1 by 20%, where R_{top} and R_{bottom} are the reflectance in crystalline and amorphous states, respectively.

3.6 Discussion

The sharp temperature dependence of optical constants (*n* and *k*) of optical switching film in layer 1 at transition temperature results in similar change of R/A/T in layer 1. Besides the sharp temperature dependence of optical constants, appropriate n, k value applicable for optical switching film is another essential criterion. According to the results shown in Figs. 3.4.1 and 3.4.2 for a thermo-chromatic film, $k<1$ and $n>2$ are needed to achieve high transmittance (~50% at amorphous state) for accessing layer 2; and $2<k<4.5$, $n>2.5$ to achieve adequate reflectance (~5% at amorphous state) and high absorption for accessing layer 1. By taking temperature dependence into account, the range of n and k is further derived and shown in Fig. 3.6.1 where the candidate materials possess $k<1$ at temperature below Tt, and n and k increase sharply above Tt, respectively.

Many potential candidates meet these requirements exhibiting semiconductor to metallic phase transitions include [3-14]:

- Vanadium oxides (VO_2).
- Superionic conductors: silver sulphide (Ag_2S) and silver selenide (Ag_2Se) and their alloys.

Moreover, candidates of optical switching layer do not limit to thermo-chromatic materials, organic materials [3-14] and others, for example, whose temperature-dependence exhibit properties as illustrated is Fig. 3.6.1, are possible candidates as optical switching films.

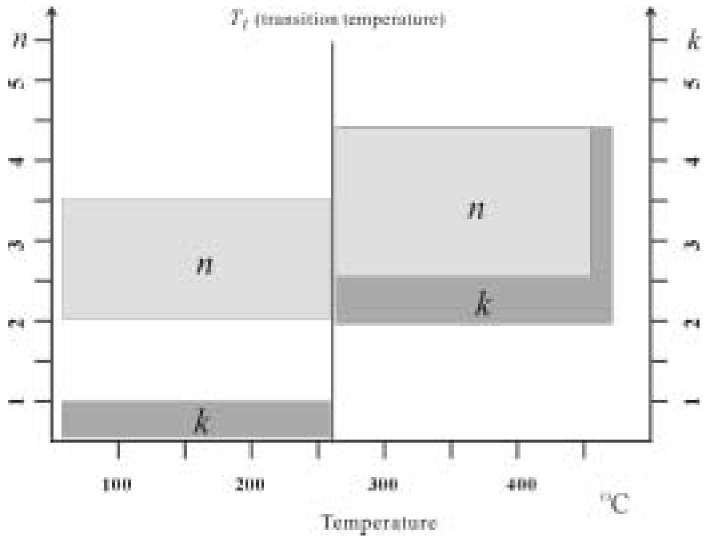


Fig. 3.6.1. Estimated ranges of candidate material for optical switching film: $2<n<3.5$ and $k<1$ as $T<T_t$; $2.5<n<4.5$ and $2<k<4.5$ as $T> T_t$.

3.7 Summary

The dual layer optical disk with optical switching layer was modeled and the following was obtained. Adding a thin thermo-induced semiconductor-to-metal phase transition optical switching layer to layer 1 results in increase of the absorption and transmittance by 10 and 30% when laser beam focuses on layer 1 and 2 of a dual layer optical disk, respectively. The study reveals that the efficiency of laser power for recording by adding an optical switching layer can be easily optimized. Moreover, the contrast of reflected signal is increased by 20%. The optical switching layer is being fabricated on a dual layer optical disk to evaluate its recording performance.

CHAPTER 4

THERMOCHROMISM OF SILVER OXIDE FOR OPTICAL SWITCHING LAYERS IN MULTILAYER OPTICAL DISK

For reading and writing on a lower targeted recording layer of volumetric optical disks, transmitted laser power is decreased by absorption and reflection of the upper layers. Thus, a layer of thermo-chromatic material, such as silver oxide, has been added as an optical switching layer next to the recording layers to modulate the optical characteristics of the recording layers by the diffraction limited laser beam during writing. The optical switching structure can reduce peak writing laser energy by 42%. Consequently, optical switching layer is promising for volumetric recording to optimize R/W performance.

4.1 Optical Switching Structure in a Rewritable-Type Dual layer Optical Disk

Many methods have been presented to increase the areal density in optical storage technologies, such as land-groove recording, short laser wavelength, large numerical aperture (NA) objective lens, and volumetric recording [4-1]. Dual-layer recording is one type of volumetric recording which can almost double the recording capacity by utilizing two recording layers. Dual-layer rewritable phase-change optical disks using four different materials were designed and reported in 1998 [4-2].

In general, the upper data layer, the first data layer seen by the incident beam, is designed to be semi-transparent to make the second data layer accessible. Therefore, a disk structure with no metallic reflector in layer 1, as shown in Fig. 4.1.1 (a), was first designed [4-2] to meet the above requirements. For writing and reading on layer 1, nevertheless, both low power absorption efficiency and lower reflected signal were resulted from this disk structure. Thus, a thermally controlled optical switching layer sandwiched between layers 1 and 2, as shown in Fig. 4.1.1 (b), is proposed to allow high absorption and high transmittance in layer 1 when the laser beam is focused on layers 1 and 2, respectively. Thermo-chromatic material undergoes a thermally induced reversible phase transition, resulting in significant changes in its optical properties [4-3]. For a dual layer optical disk with a thermo-chromatic material added in the structure, as shown in Fig. 4.1.1 (b), layer 1 behaves like a thermally induced optical switch. When the laser beam is focused on layer 1, its temperature is increased and layer 1 becomes highly absorptive. In addition, previous study also revealed that the efficiency of laser power for recording with an optical switching layer could be easily optimized. [4-4]

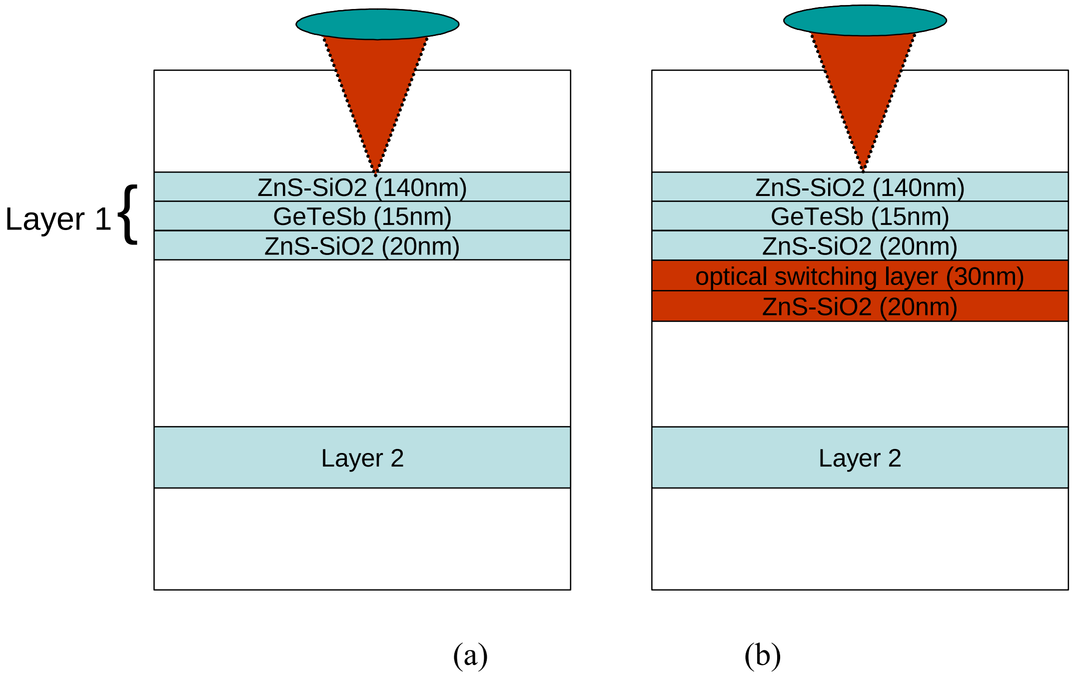
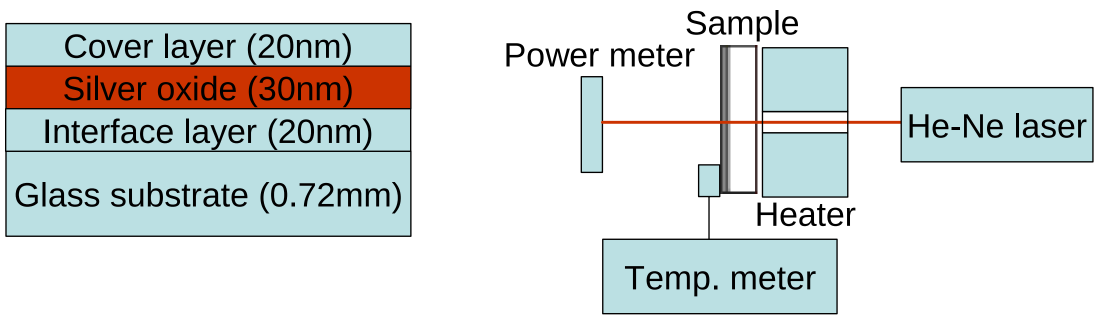


Fig. 4.1.1. Schematics of a dual layer optical disk with (a) no metallic reflector and (b) an optical switching layer structure.

4.2 Properties of Thermochromism Material

Silver oxide, a potential thermo-chromatic material, was chosen for verifying the optical switch function in the dual layer disk. Sliver oxide samples were prepared in a magnetron sputtering system with Ar-O_2 reactive sputtering on glass substrates. The 20-nm thick silver oxide film was sandwiched between two 20-nm thick ZnS-SiO_2 protection and interface films, as shown in Fig. 4.2.1 (a). A thermo-photometric apparatus was constructed to evaluate the thermochromism of silver oxide. Samples were fixed on a hot plate as illustrated in Fig. 4.2.1 (b). A small hole was cut in the center of the hot plate for the laser beam to pass through the sample and reach the power meter. Samples prepared under different sputtering conditions were labeled as Ar/O_2: gas flow ratio in the unit of SCCM during the sputtering process.



(a) (b)

Fig. 4.2.1. (a) Sample structure of silver oxide film and (b) thermo-photometric apparatus.

Measured transmittance of samples with fixed oxygen and argon gas flow rates is shown in Fig. 4.2.2 (a) and (b), respectively. The curves in the figure are variations of transmittance *T* for temperature up to 210 ^{o}C. The reason for the drastic change of transmittance upon temperature is the decomposition of AgO_x to Ag_2O phase. This decomposition of silver oxide had been demonstrated by Waterhouse *et al*. and is given by, [4-5]

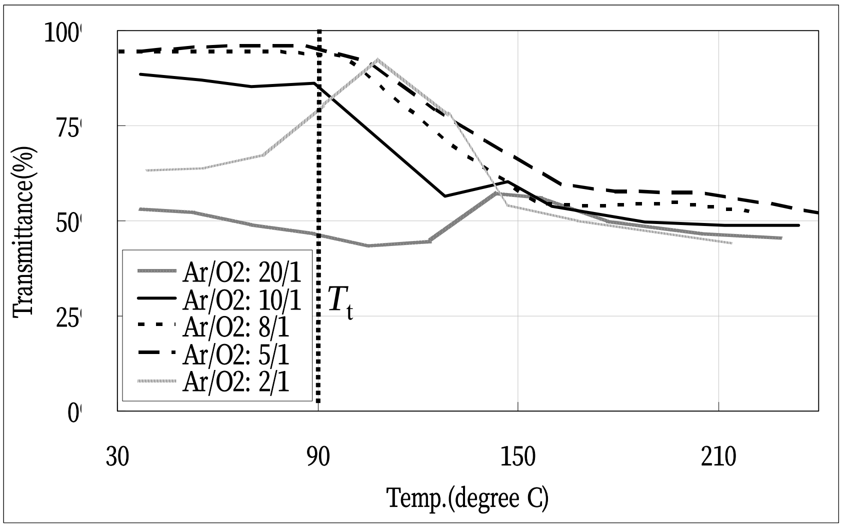
$$AgO_x \rightarrow AgO_2 + xO_2 \quad (4\text{-}1)$$

$$4AgO_2 \xrightarrow{T>100^o C} 2Ag_2O+3O_2 \quad (4\text{-}2)$$

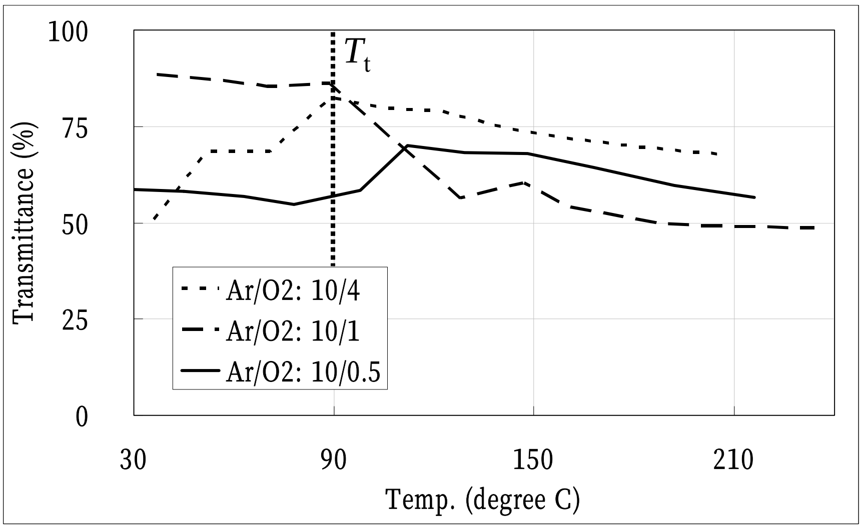
$$2Ag_2O \xrightarrow{T>160^o C} 4Ag+O_2 \quad (4\text{-}3)$$

The silver oxide (AgO_x) decomposes to silver particles and oxygen as the temperature go beyond 160 ºC. The reactions can be reversible if the silver oxide thin film is sandwiched between protective layers. Hence, thermo-chromatic optical switching can be realized by this sandwiched structure. In addition, transmittance changed upon temperature was observed in the higher oxygen contained samples with Ar/O_2=2/1 and 10/4. The reason is supposed that too much oxygen molecule was released during the heating process and affected the crystal structure of silver oxide. The sample with Ar/O_2=8/1 that exhibited large transmittance drop from 95% to 52% was chosen as the optical switching layer in the following experiments.

Transition speed of silver oxide films sandwiched between protective layers was studied by using a pulsed laser. An acoustic-optical modulator was used to modulate a He-Ne laser and generate kilo-Hertz laser pulses. The laser pulses were then split into a monitor beam and a heating beam by a beam splitter. The heating beam was focused by a 0.8 NA (numerical aperture) objective lens on the silver oxide sample to achieve a small spot, which leads to high temperature in the silver oxide layer. The monitor beam and transmitted beam were collected by detectors A and B, respectively. A digital oscilloscope was used to record time traces and process detected signals, as shown in Fig. 4.2.3. Experimental results of the single-shot-pulse response of this optical switching structure, as shown in Fig. 4.2.4, show no significant time delay between the monitor signal and transmittance change, defined by signal B/signal A. It also suggests that the ratio of signal B to signal A is higher when the peak power of the heating pulses is higher. These results exhibit that the fast response time of the optical switching layer can be applicable to optical storage. In addition, a pump-probe experiment setup can measure the transition speed of silver-oxide sample quantitatively. Detail descriptions of the measurement can be found in reference [4-6].



(a)



(b)

Fig. 4.2.2. Temperature dependence of optical transmittance of silver oxide thin film. The curves depict measured results with different argon and oxygen ratio. In (a) argon gas flow rate was increased from 2 to 20 while oxygen gas flow rate was 1 SCCM; and (b) oxygen gas flow rate was increased from 0.5 to 4 while argon gas flow rate was 10 SCCM.

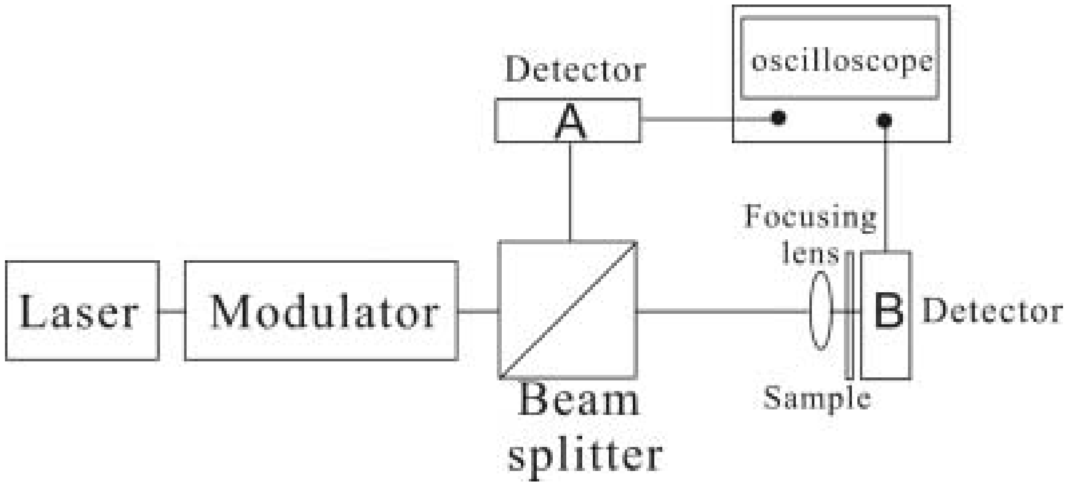


Fig. 4.2.3. Schematics of response time measurement of optical switching structure.

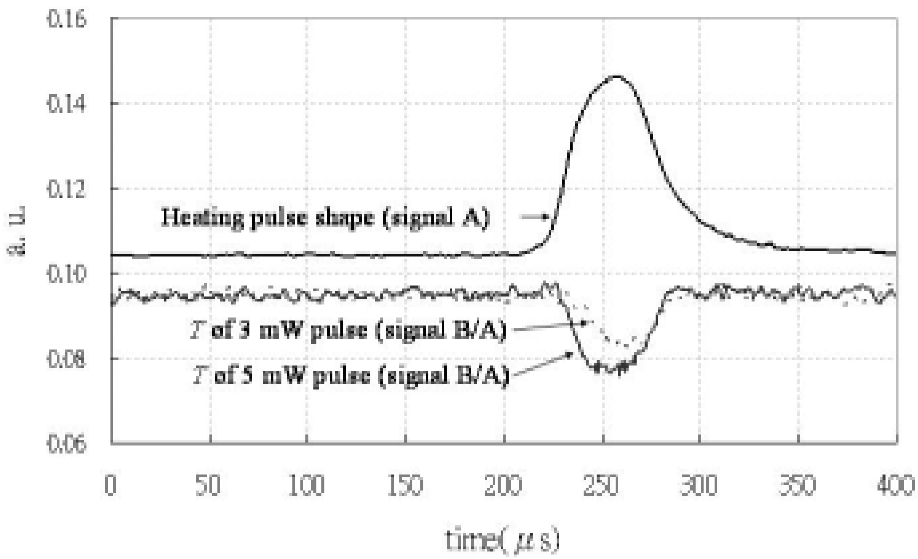
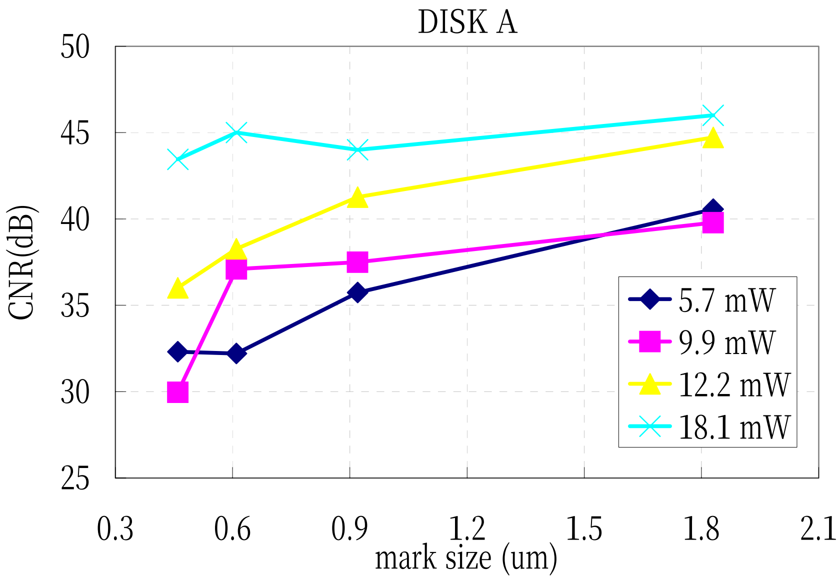


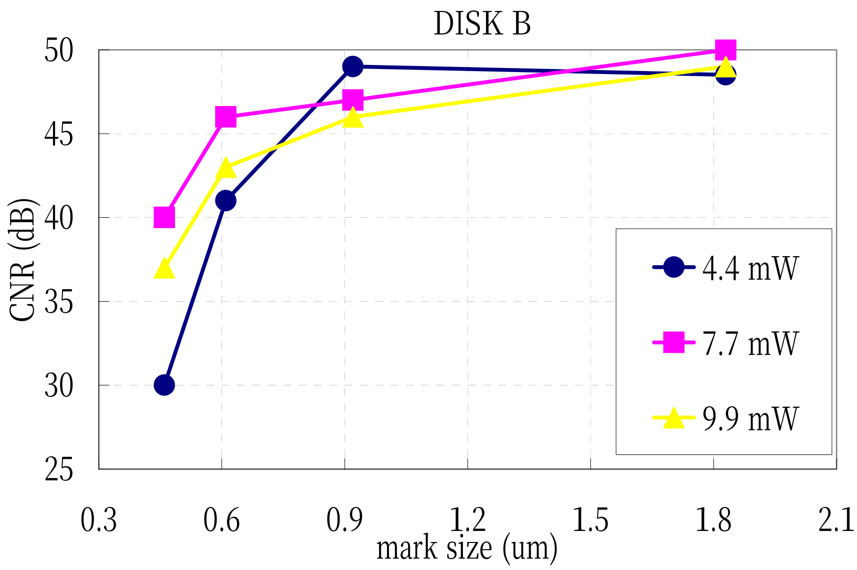
Fig. 4.2.4. Transmittance changes due to a writing pulse in the response time experiment.

4.3 Dynamic Tests

To evaluate the writing performance of the disk with optical switching structure, sample disks "A" and "B" with structures shown in Fig. 4.1.1 (a) and (b), respectively, were prepared. Disk "A", a reference disk, has a structure of 80nm ZnS-SiO_2/15nm GeTeSb/ 20nm ZnS-SiO_2 for layer 1. In addition to the structure of disk "A", an additional optical switching structure of 30nm optical switching layer (silver oxide)/ 20nm ZnS-SiO_2 was fabricated as disk "B". Transition temperature (T_t) of sample (Ar/O_2:8/1) is about 90 ^oC as shown in Fig. 4.2.2 (a), temperature on the optical switching layer could be raised over transition temperature during recording (over 400 ^oC). The result reveals that optical switching layer could change recording characteristics of layer 1. The dependence of carrier-to-noise ratio (CNR) on the mark size of two sample disks was measured and shown in Fig. 4.3.1 by using a dynamic tester. The linear velocity was 7.4 m/s and the laser power was modulated by a single frequency pulse train from 2 to 8 MHz with 50% duty cycle. For sample disks "A" and "B", CNRs of 45 dB or higher were obtained at a peak power of 18.1 and 7.7 mW, respectively. The peak writing power in the disk "B" was reduced by 42% due to the additional optical switching layer. However, CNR dropped when the peak writing power increased, maybe due to that excessive laser energy overheated and slightly damaged the recording material. The result shows that, higher laser energy efficiency is obtained on a disk with an additional optical switching structure. The CNR as functions of direct overwrite (DOW) cycles with mark size of 0.6 μm of disks are shown in Fig. 4.3.2. The recording performance maintained on disk "B" before 2000 DOW cycles, which is applicable for DVD-RW applications.



(a)



(b)

Fig. 4.3.1. CNR as functions of the mark size and peak write power of a disk (a) without and (b) with an optical switching layer.

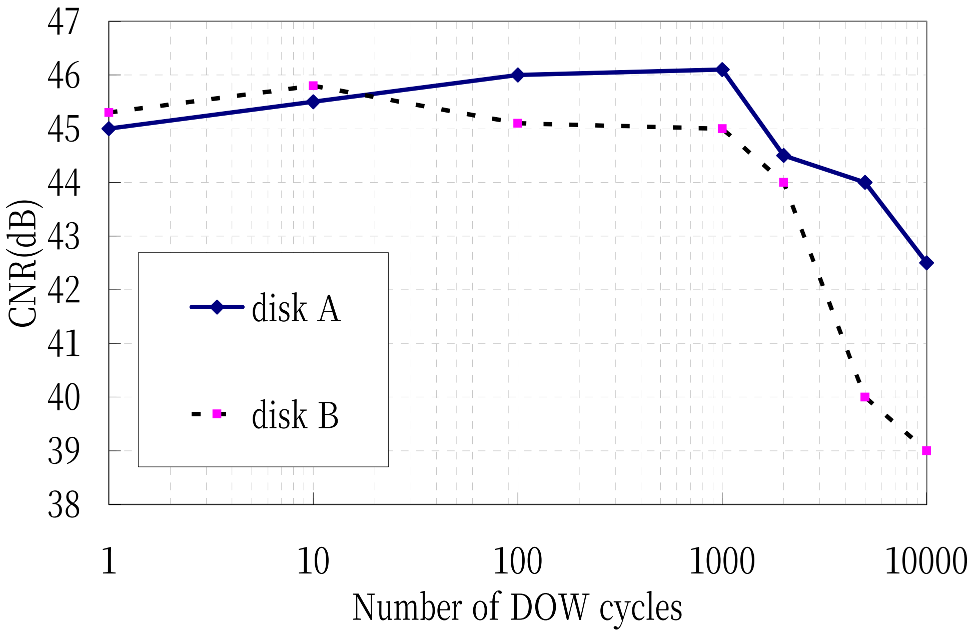


Fig. 4.3.2. CNR as functions of number of DOW on disks “A” and “B”.

The above results show the peak writing power of a disk with additional optical switching structures can be reduced, consequently, the number of recording layers on a disk substrate can increase. To write on the lower recording layer, the output laser power needs to be properly increased to compensate for the loss in transmitting through the upper recording layers. To record lower recording layers, the output laser power was raised by a factor of *T*, the transmittance of the upper recording layers. The required writing power to record on the lower recording layer in both disks as a function of factor *T* is shown in Fig. 4.3.3. The measured transmittance in the as-deposited state of the disks “A” and “B” are 63.3% and 58.6%, respectively. Thus, average transmittance of the first recording layer of 60% was chosen in the following calculations. If the laser diode in the drive can provide 30 mW peak writing power, then 18 and 28 mW laser power is required for recording on the two recording layers, respectively. If a four-layer disk with optical switching structures in each layer, laser power of 7, 11, 17, 27 mW is calculated to record on the four recording layers, respectively. Thus, multiple recording layers with optical switching structures can increase data capacity on a disk, as illustrated in Fig. 4.3.4.

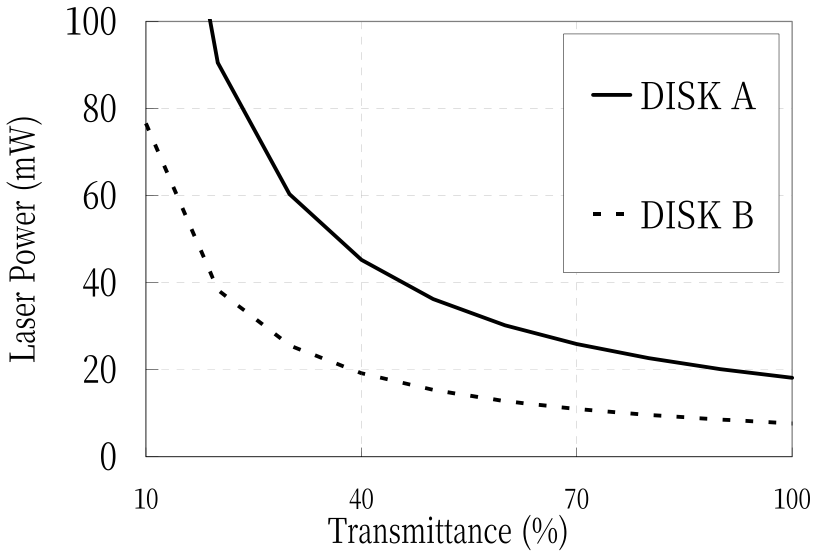


Fig. 4.3.3. Simulated writing power to record on the second recording layer in both disks as a function of transmittance of the first recording layer.

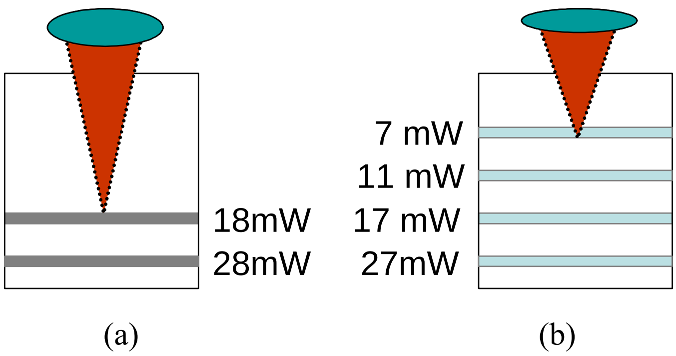


Fig. 4.3.4. Simulated writing power to record on each recording layer in disks (a) without and (b) with optical switching structures.

4.5 Summary

Optical switching layers in volumetric optical disks were proposed to modulate the optical characteristics during writing. Materials, whose transmittance decreases with temperature, such as thermo-chromatic materials, are potential candidate as an optical switching layer. The silver oxide sample exhibiting transmittance change by 43% with increased temperature was chosen for the optical switching layer in the disk. Experimental results showed the peak writing power could be reduced by 42% in the disk with an additional optical switching layer. Furthermore, Optical switching layer is promising for volumetric recording to optimize the writing laser power, thus R/W performance.

CHAPTER 5

WRITE-ONCE VOLUMETRIC OPTICLA DISK USING TRANSPARENT RECORDING MATERIAL WITH AN OPTICAL SWITCHING LAYER

A volumetric optical disk having multiple transparent films with optical switching layers is proposed as a recordable medium to increase the number of recording layers. In the disk, an optical switching layer is adopted to reduce laser energy decay and increase recording sensitivity for reading and recording, respectively. A well-defined deformation area (mark) with submicron to nanometric dimensions can be yielded precisely on the transparent films by a focused laser beam. The peak writing power of 7 mW for a four-layer recordable medium, fabricated by molding and spin bonding techniques, was demonstrated experimentally as an example. The proposed volumetric disk can achieve a higher recording capacity by using conventional optical pickup units.

5.1 Introduction

As the demand for storage capacity continually grows, data storage technologies are being driven to achieve higher capacity, higher readout and recording bit rate, and faster access time. The recordable optical disk, as a two-dimensional optical storage medium, is currently the most widespread physical format for optical storage. A promising technique has been developed to increase the volumetric data density of optical disks by including a third physical dimension, using a multilayer recording structure, i.e., by axially stacking a number of recording layers. However, issues such as interlayer crosstalk, low laser energy transmittance, and absorption exist in such a disk [5-1]. Therefore, the structure with an optical switching layer in a volumetric optical disk was introduced [5-2~3] to resolve these issues. In this chapter, a disk structure of multiple transparent films with an optical switching layer as recordable media is demonstrated to increase the number of recording layers in a volumetric optical disk.

5.2 Disk Design Concept

In a multilayer optical disk, laser energy is decreased by the presence of out-of-focus recording layers. The total number of recording layers is therefore limited by the fixed laser power of the pickup. An intensity-dependent nonlinear optical structure as an optical switching layer added to each recording layer, as shown in Fig. 5.2.1, was proposed to modulate the absorption and transmission of light in the recording layers, depending on whether the laser is focused on it or not. In addition, the conventional low-transmittance recording material was replaced by a transparent one (polycarbonate), as illustrated in Fig. 5.2.2, to improve laser energy efficiency, suppress the interlayer crosstalk, and increase the total number of recording layers. Specifically, this simplified structure offers a three-dimensional optical disk with significantly decreased crosstalk, large number of inexpensive recording layers on a substrate, and reduced reading/recording laser power.

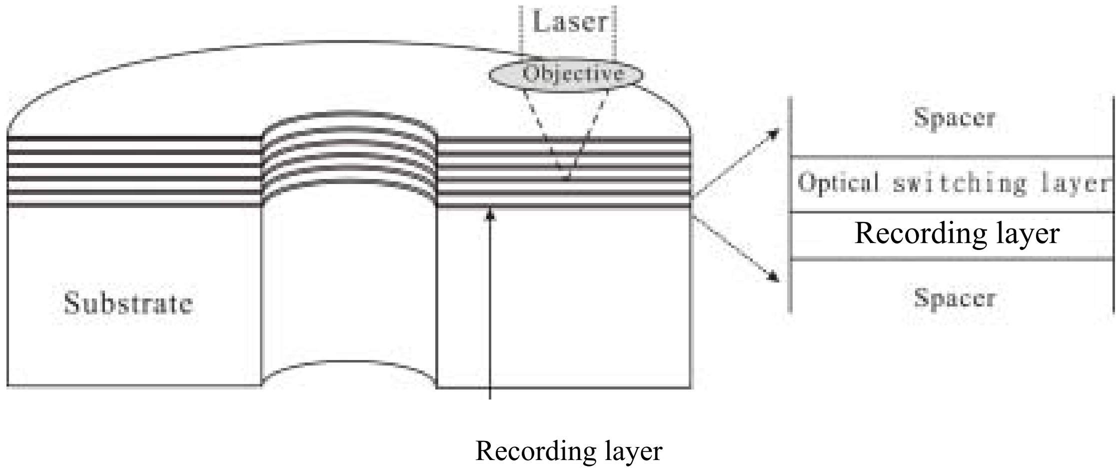


Fig. 5.1.1. Schematic diagram of an optical disk with optical switching layers.

As the disk is accessed by a pickup, the interactions between recording layers and the focused laser spot are divided into three cases: (a) at very low light intensity, (b) reading, and (c) writing modes, as shown in Figs. 5.2.3 (a)-(c), respectively. To read or record data marks on the recording layers, optical switching layers should have the following nonlinear characteristics in various modes:

(a) No nonlinear phenomenon occurs as the optical switching layer is illuminated by a very low intensity out-of-focus spot. The recording layers are a high transmittance state to suppress the interlayer crosstalk.

(b) Larger reflected signals (more than 10%) can be obtained because the nonlinear absorption phenomenon occurs and enhances its reflectivity in the focused spot area.

(c) Nonreversible thermally deformed materials, such as polycarbonate (PC) or polymethyl methacrylate (PMMA), are deformed if a higher power is applied. A write-once submicron mark can be recorded on the transparent materials.

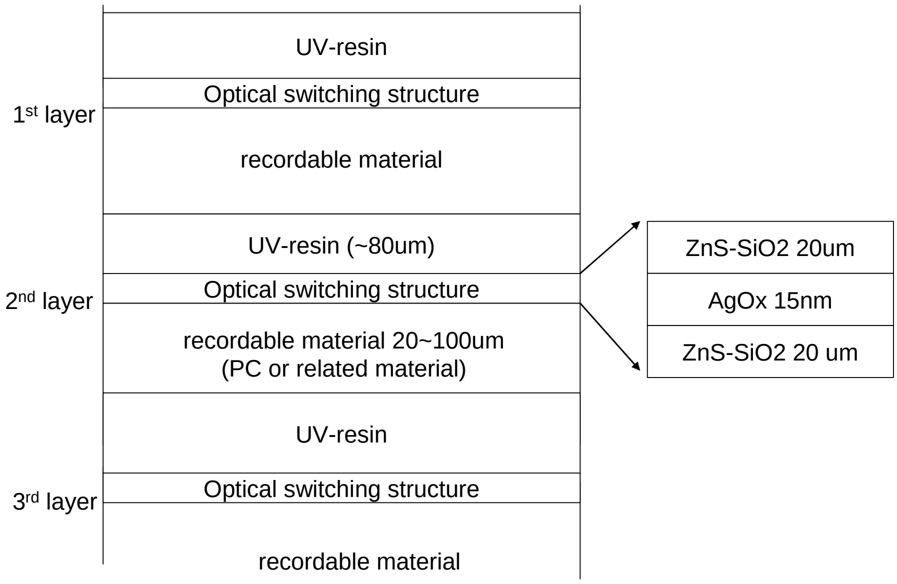


Fig. 5.2.2. Schematic of a multilayer disk structure using transparent recordable material with an optical switching layer.

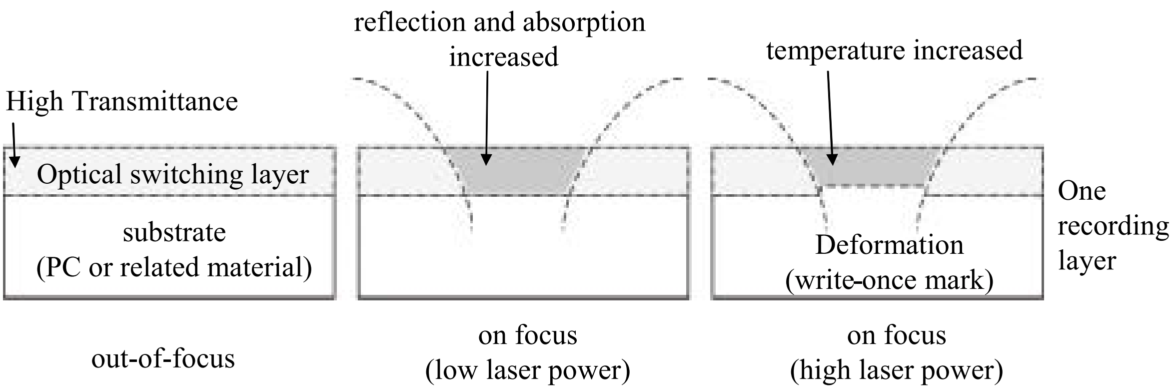


Fig. 5.2.3. Working principle of one recording layer in a write-once multilayer optical disk with optical switching layers: (a) out-off-focus, (b) reading, and (c) recording.

5.3. Optical Nonlinearity of Triple-Layer Silver Oxide Structure

A triple-layer silver oxide structure, $ZnS-SiO_2/AgO_x/ZnS-SiO_2$, with large optical nonlinearity [5-4~5] was used as the optical switching layer in the disks. Nonlinear optical properties of the triple layer silver oxide samples were observed as a function of oxygen flow ratio during deposition. The z-scan technique [5-6] shown in Fig. 5.3.1 was used to study the nonlinear optical properties. A picosecond pulse diode laser (λ=633 nm) was adopted as the light source to prevent heating the sample and pulsed at the repetition rate of 40 MHz. A high numerical aperture objective lens (NA=0.85) was used for illuminating a focused area. Transmitted light was detected by a detector. A digital oscilloscope was used to record time traces of detected average transmitted power.

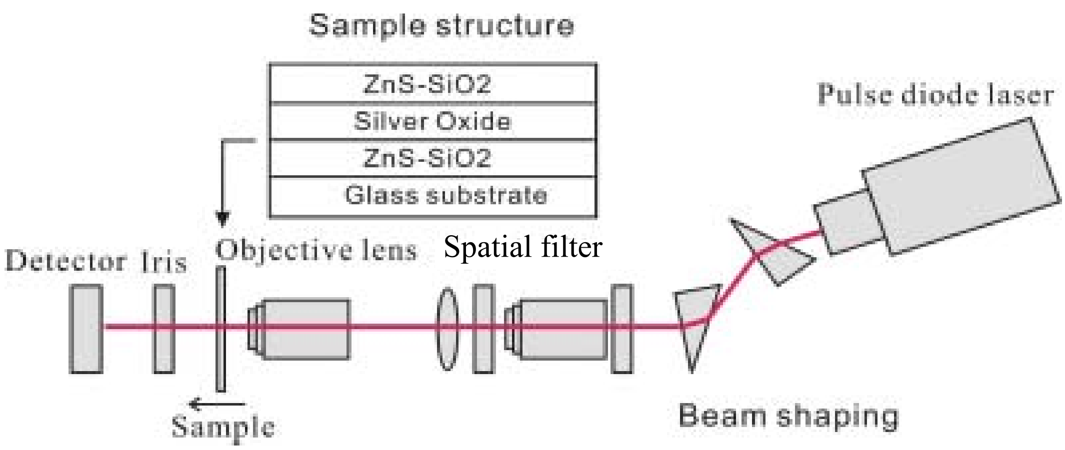
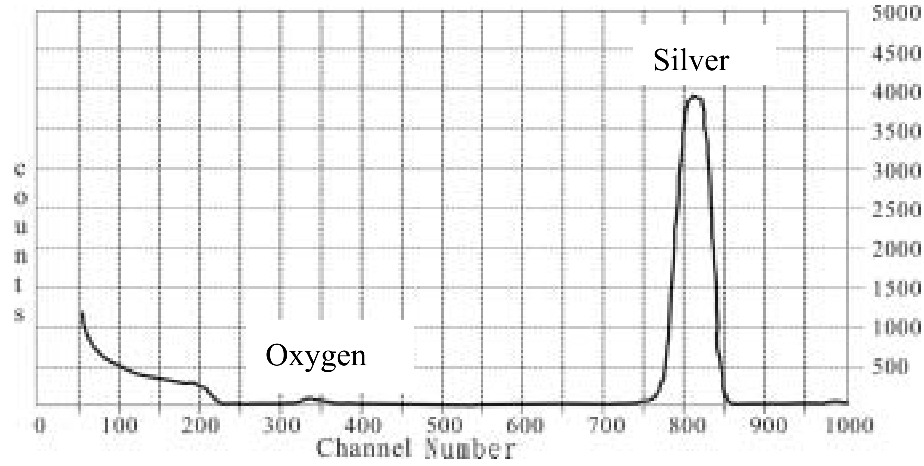


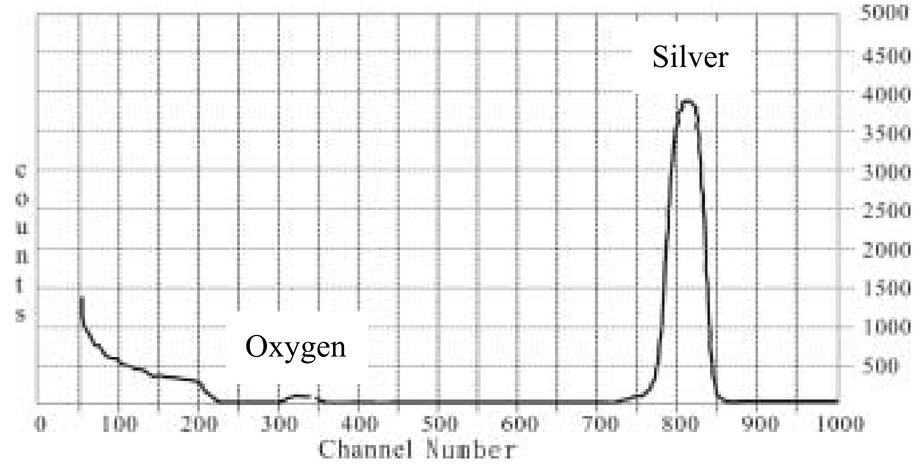
Fig. 5.3.1. Experimental setup for the silver oxide nonlinearity measurement.

Three samples under oxygen flow ratios of Ar/O_2:10/0.5, 10/1, and 10/2 in units of standard cubic centimeter per minute (SCCM), pressure of 6 millitorr, and power of 50 watt were measured. Rutherford backscattering spectrometry (RBS) was used to analyze the silver to oxygen ratio of silver oxide samples prepared under different conditions. The obtained spectra are shown in Fig. 5.3.2. The determined silver to oxygen ratios for samples Ar/O_2:10/0.5, 10/1, and 10/2 are $AgO_{0.31}$, $AgO_{0.59}$, and $AgO_{0.71}$, respectively.

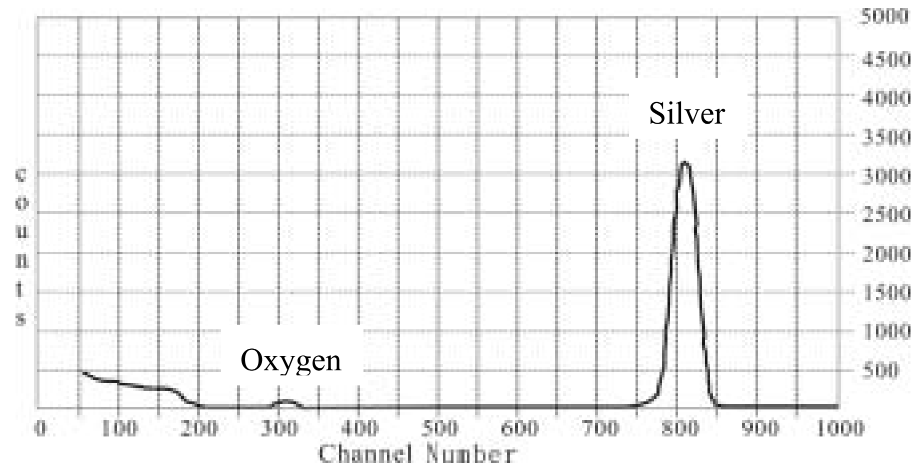
The normalized transmittance in the z-scan experiment is shown in Fig. 5.3.3. In the experiments, samples were irradiated by the laser energies listed in Table I. In Fig. 5.3.3 (a), sample $AgO_{0.31}$ shows the lowest linear transmission and exhibits a nonlinearity that is a function of laser power. A low-power behavior (below 61.8 mW peak), indicated by curves A and B in Fig. 5.3.3 (a), shows a slight increase in absorption as irradiance increases when the sample is near the focal point. A higher-power behavior, as indicated by curves C and D in Fig. Fig. 5.3.3 (a), shows an increase in transmittance as the sample draws closer to the focus. One possible explanation is that a tiny hole was formed, which increased the transmittance on the sample due to the high laser energy. The hole did not collapse when the laser energy was removed, so the sample was permanently damaged. However, sample $AgO_{0.59}$ exhibits a different nonlinear behavior which is not a strong function of laser pulsing. Transmittance decreases as the sample approaches the focus for all laser powers in approximately the same proportion, as shown in Fig. 5.3.3 (b). The nonlinear coefficient is positive in this case, and the magnitude of the coefficient decreases with increased laser power. For sample $AgO_{0.71}$, which has the highest oxygen content, the nonlinear characteristics are more similar to those of sample $AgO_{0.31}$ than to those of sample $AgO_{0.59}$, as shown in Fig. 5.3.3 (c), but the effect is not as strong. In this case, the result was nonreversible; the samples were permanently damaged at all power levels. The results also reveal the high dependence of the nonlinearity on the oxygen content of the sandwiched silver oxide sample.



(a)

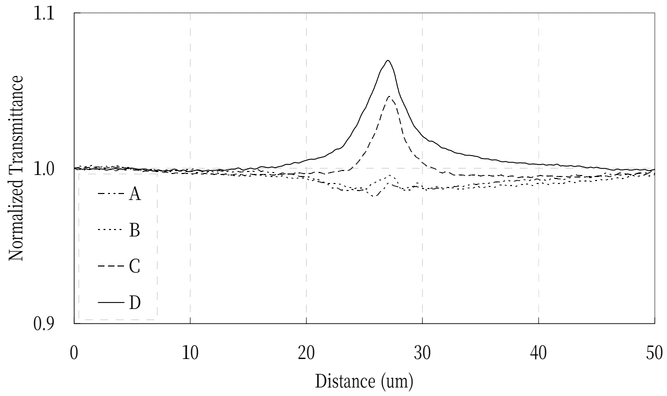


(b)

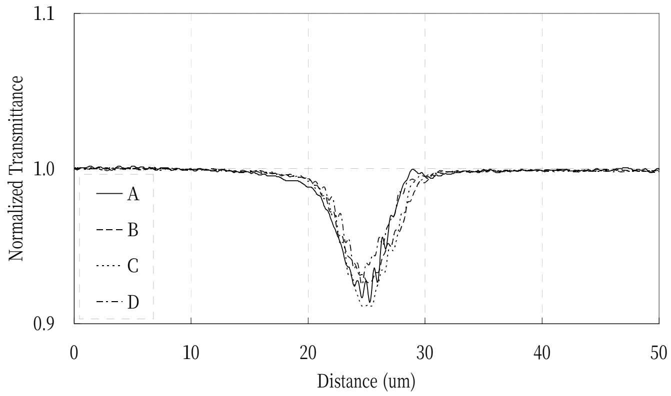


(c)

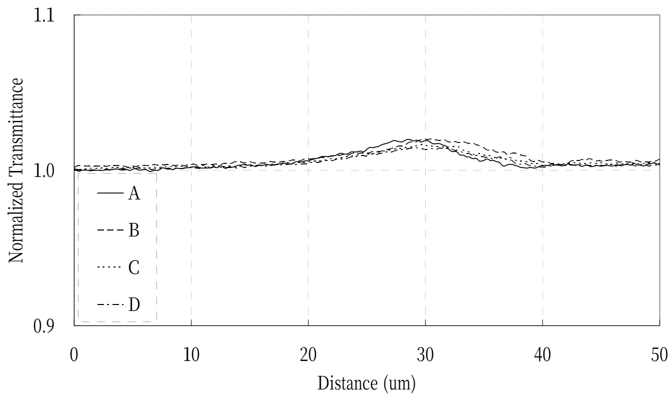
Fig. 5.3.2. RBS spectra for silver oxide samples processed under various Ar/O_2 ratios: (a) 10/0.5, (b) 10/1, and (c) 10/2.



(a)



(b)



(c)

Fig. 5.3.3. Nonlinearity obtained by z-scan of samples Ar/O_2: (a) 10/0.5, (b) 10/1, and (c) 10/2.

Table I. The laser parameters in the z-scan experiments.

	Ave. power (mW)	Peak power (mW)	Pulse width (ps)
A	0.1	43.4	35
B	0.2	61.8	49
C	0.7	85.5	49
D	1.5	104.5	366

5.4 CCD Images at Focus

In order to better understand the nonlinear effect, the iris and detector in the z-scan experiment were replaced by a 0.6 NA objective lens and the laser light was collected on a charge coupled device (CCD), as shown in Fig. 5.4.1. The light pattern observed in Fig. 5.4.2 (a) is the CCD image of a simple Gaussian-like distribution in the case of no sample. The behavior of sample $AgO_{0.59}$ at focus is shown in Fig. 5.4.2 (b). The light distribution exhibits multiple lobes due to the nonlinear absorption of the sample. For sample $AgO_{0.71}$, no significant change in the distribution is observed due to the lack of nonlinear response, as shown in Fig. 5.4.2 (c). Therefore, the triple-layer silver oxide, $ZnS\text{-}SiO_2$/ $AgO_{0.59}$/$ZnS\text{-}SiO_2$, with the large optical nonlinearity was chosen as the optical switching layer in the following experiments.

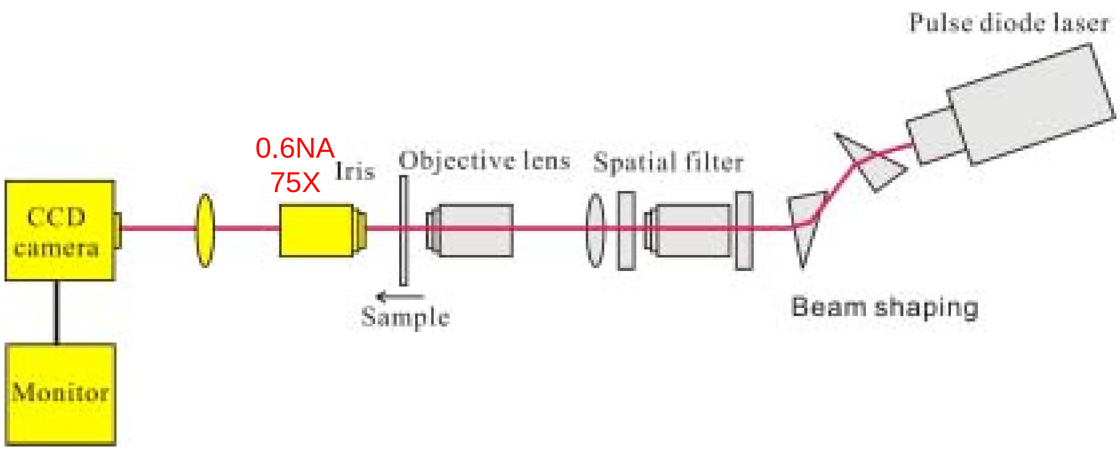
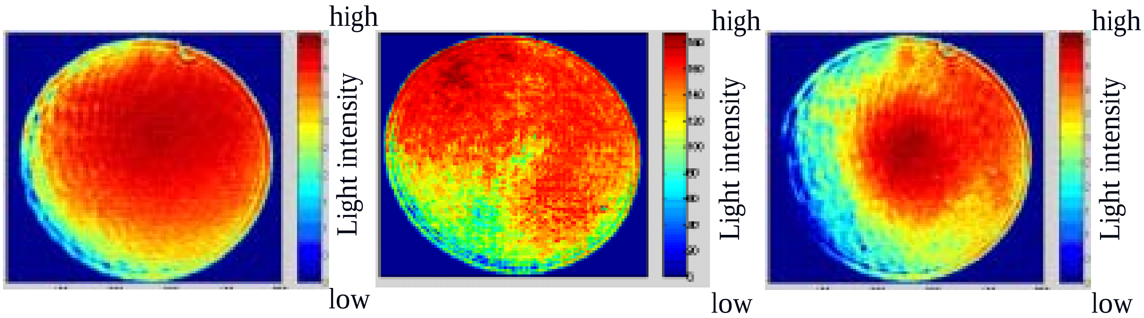


Fig. 5.4.1. Experimental schematics for the light pattern observation through silver oxide sample.



(a) (b) (c)

Fig. 5.4.2. Light patterns as the laser passes through (a) no sample, and silver oxide samples of (b) $AgO_{0.59}$ and (c) $AgO_{0.71}$ at the focus.

5.5 Writing on a Four-Layer Sample Disk

A four-layer sample disk was fabricated to evaluate the feasibility of a write-once multilayer optical disk using a transparent recordable material with an optical switching layer and is shown in Fig. 5.5.1. The disk is composed of a substrate and multiple stacked recording layers consisting of polycarbonate films and a triple-layer silver oxide structure, 20 nm ZnS-SiO2/ 15 nm $AgO_{0.59}$/ 20nm ZnS-SiO2. The writing experiment was conducted using a microscope system equipped with a piezoactuator (PZT) stage, the experimental setup is shown in Fig. 5.5.2. In addition, the laser spot focused on the recording layer was controlled manually and a 20 um movement was achieved on the sample. Writing powers on the recording layers were 1.5, 2.5, 4.2, and 7 mW. A clear written pattern on the first recording layer was observed by a 100x microscope objective, shown in Fig. 5.5.3 (a). The recorded marks on layers one to four were read back using a 0.85 NA objective lens, shown in Figs. 5.5.3 (b)-(e), respectively.

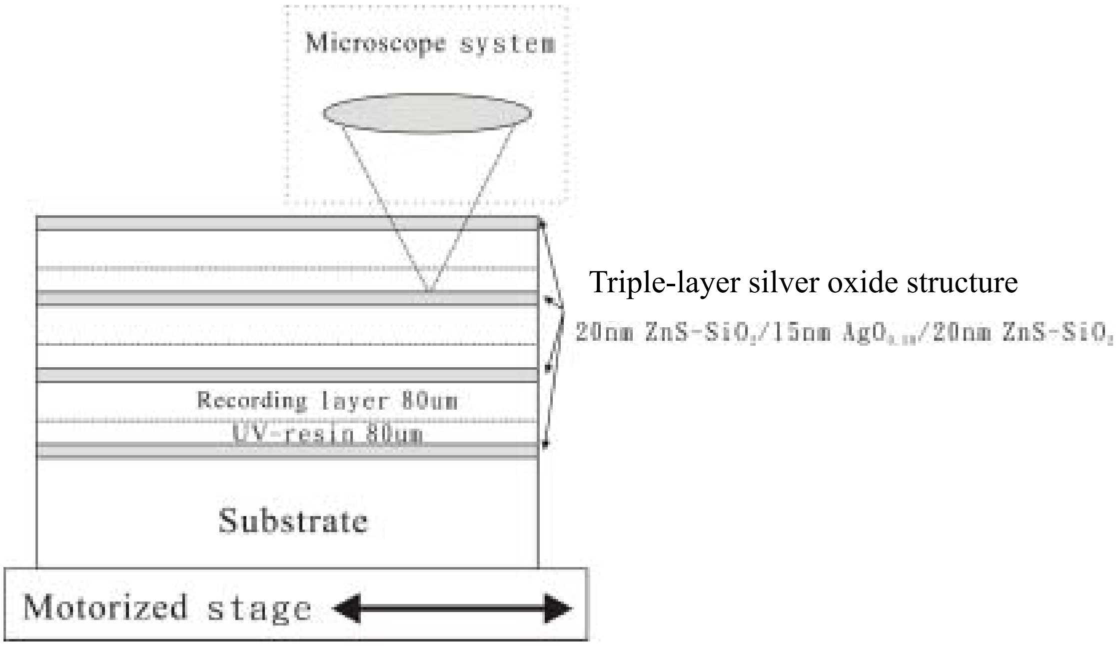


Fig. 5.5.1. Four-recording-layer sample structure and writing experimental setup.

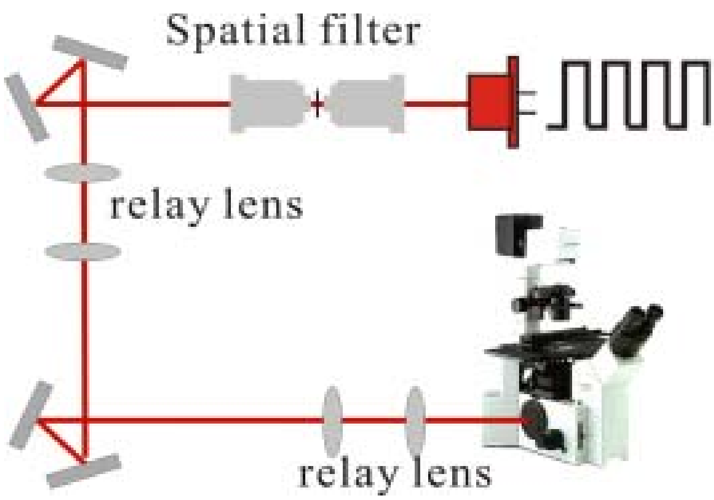


Fig. 5.5.2. A microscope-based testing setup.

With a multilayer disk system, there is a possibility that marks from more than one data layer can be simultaneously detected. This interlayer crosstalk complicates the readout process. To minimize crosstalk, each layer is separated by more than 50 um. The focused spot size on each layer must be as small as possible to maximize capacity.

Spot size is increased by spherical aberration. The substrate affects the amount of spherical aberration introduced by its thickness. A poor readout signal was obtained, as shown in Fig. 5.5.2 (e), because the focused spot size on the fourth layer was increased by spherical aberration. Milster et al. proposed a Burch-type objective lens to compensate for the spherical aberration induced by the substrate thickness from 0.6 to 1.2 mm [5-7]. Using the Burch-type objective lens, high-transmittance recording layer design, and thin polycarbonate films in the disk, it is possible to achieve more than ten recording layers on a disk substrate.

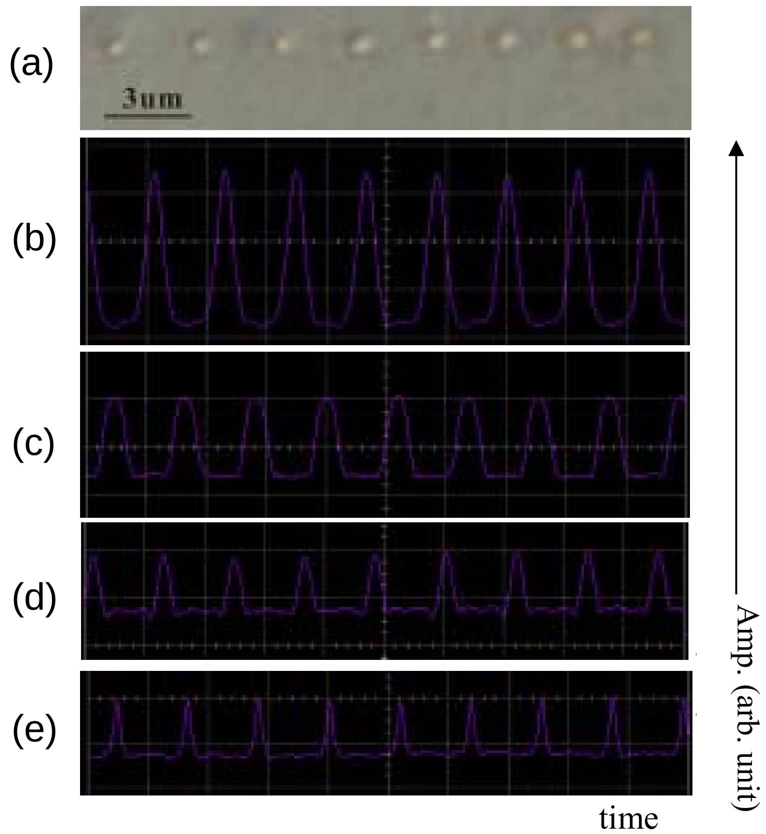


Fig. 5.5.3. (a) Written marks, observed using a microscope, on the first recording layer, and (b) to (e) readout signals of layers one to four, respectively.

5.6. Summary

A write-once multilayer optical disk using transparent recordable materials and nonlinear optical switching layers is proposed to realize large data capacity on one disk substrate. In such a disk, the nonlinear material is designed to modulate the laser energy distribution on each recording layer. The obtained triple layer silver oxide structure with large transmittance decrease is a candidate for the write-once multilayer optical disk. A four-layer recordable sample disk was designed and fabricated for the writing/reading test. A writing power of 7 mW was required to write data marks on the fourth layer. Therefore, a transparent recordable material with an optical switching layer can be used to reduce the writing laser power and increase the number of recording layers in the volumetric disk.

CHAPTER 6

PERFORMANCE OF WRITE-ONCE MULTILAYER OPTICAL DISK USING TRANSPARENT RECORDING MATERIAL WITH AN OPTICAL SWITCHING LAYER

A volumetric optical disk having multiple transparent films with optical switching layers is demonstrated as a recording medium to increase the number of recording layers. In the disk, the optical switching layer is adopted to reduce laser energy decay and increase reading and recording sensitivity. Well-defined marks of about 100 nm in depth can be yielded precisely on the transparent films by a focused laser beam. Writing and reading of a four-layer recordable disk, fabricated by molding and spin bonding techniques, were demonstrated experimentally. The presented volumetric disk can achieve a high recording capacity with conventional optical pickups.

6.1 Introduction

As the demand for storage capacity continually grows, data storage technologies are being driven to achieve higher capacity, higher readout and recording bit rate, and faster access time. The recordable optical disk, as a two-dimensional optical storage medium, is currently the most widespread physical format for optical storage. A promising technique has been developed to increase the volumetric data density of optical disks by axially stacking a number of recording layers in the third physical dimension. However, issues such as interlayer crosstalk, low laser energy transmittance, and absorption exist in such a disk [6-1]. To resolve these issues, an optical switching layer was introduced in a volumetric optical disk.[6-2~3] In this paper, a disk structure with multiple transparent films and optical switching layers as the recording media is demonstrated to increase the number of recording layers in a volumetric optical disk.

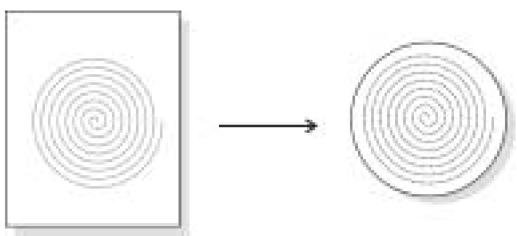
6.2 Disk Design

In a multilayer optical disk, laser energy is decreased by the presence of out-of-focus recording layers. The total number of recording layers is therefore limited by the maximum laser power of the pickup. A disk structure with an intensity-dependent nonlinear optical switching layer added to each layer, as shown in Fig. 5.1.1, is proposed to modulate the absorption and transmission of light in the recording layers. In the disk, the conventional low-transmittance recording material was replaced by a transparent PC sheet with thickness of 80 um to improve laser energy efficiency, suppress the interlayer crosstalk, and increase the total number of recording layers. A triple-layer silver oxide structure, 20nm ZnS-SiO_2/ 15nm $AgO_{0.59}$/20nm ZnS-SiO_2, [6-4] was chosen as the optical switching layer in the disks for its large optical nonlinearity [6-5]. The cross-sectional view of the write-once multilayer disk is illustrated in Fig. 6.2.3. Specifically, this simplified structure offers a three-dimensional optical disk with significantly decreased crosstalk, large number of inexpensive recording layers on a substrate, and reduced reading/recording laser power [6-4].

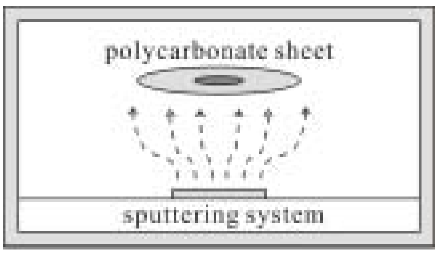
6.3 Disk Fabrication and Testing

The disk was fabricated by stacking the recording layers as illustrated in Fig. 6.3.1. First, the land/groove structure for tracking was transferred from a DVD-R (Digital Versatile Disk-Recordable) stamper to an 80 um thick PC sheet by a molding process. A clear transferred pattern on the PC sheet can be observed by an atomic force microscope (AFM), as shown in Fig. 6.3.2. Next, the PC sheets were cut to a round shape and then the triple layer silver oxide structure, functioning as an optical switching layer, was deposited by the sputtering process. Then, a spacer layer consisting of a UV-curable resin was applied by spin-coating on a 0.6 mm thick DVD substrate. Subsequently, the recording layers were bonded by spin bounding. After UV curing, a write-once multilayer optical disk was fabricated.

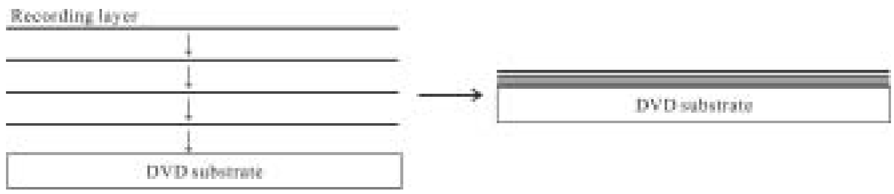
(a)



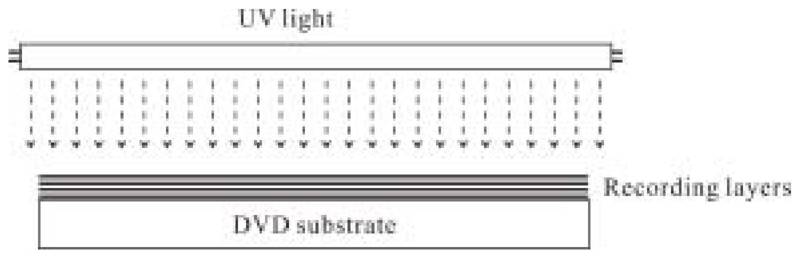
(b)



(c)



(d)



(e)

(f)

Fig. 6.3.1. Schematic illustration of the fabrication process for the multilayer disk. (a) Replication of groove structures on the 80um thick PC sheets. (b) Cut the PC sheets into round shape. (c) Deposit optical switching layers onto PC sheets by sputtering. (d) Stack recording layers on a 0.6mm thick DVD substrate. (e) UV curing. (f) A multilayer disk.

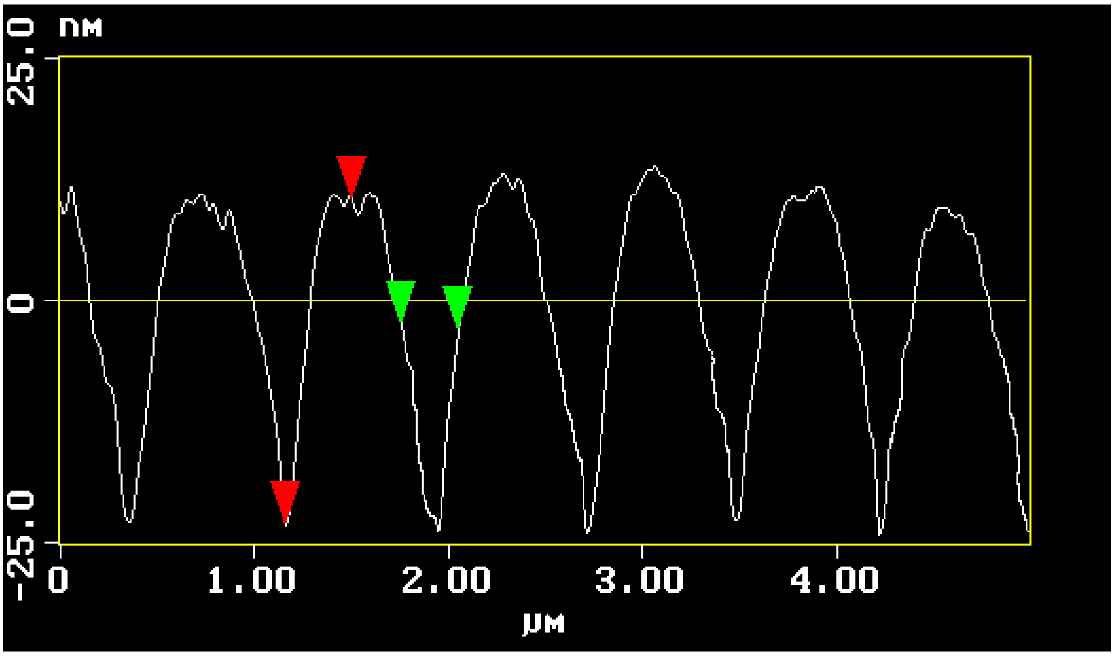


Fig. 6.3.2. AFM profile of transferred land/groove structure on the thin PC sheet.

A four-layer sample disk was fabricated to evaluate the feasibility of write-once multilayer optical disk using transparent recording material with an optical switching layer. The disk was composed of a substrate and multiple stacked recording layers consisting of PC films and triple-layer silver oxide structure, 20 nm ZnS-SiO2/ 15 nm $AgO_{0.59}$/ 20 nm ZnS-SiO2. A dynamic disk tester using a 0.6 NA (numerical aperture) objective at 650 nm wavelength was used to analyze its read/write performance. Besides, the spherical aberration caused by the diverse spacer thickness while focusing through the recording layers can be corrected by the disk testing system [6-7].

6.4 Dynamic Testing Results of Multilayer Optical Disk

6.4.1 Dynamic Tester

A commercial dynamic disk testing system, VersaTest-1 by TUI optics Co. Ltd., was used for testing the multilayer optical disks. This dynamics testing system is achromatic within the wavelength range 440–690 nm, allowing any light source in this range to be utilized for read/write experiments. In addition, the system accepts disks with substrate thicknesses ranging from 0 to 1.2 mm. Focus-error detection is based on the astigmatic method, and the primary track-error detection scheme is the push–pull method. The RF (radio frequency) data signal and the focusing and tracking servo signals are all derived from the same detectors, thus allowing the optical power returning from the disk to be used in its entirety for these multiple purposes. The detection channel consists of two high-speed quad detectors mounted on the two arms of a differential detection module. By combining the various outputs of these detectors it is possible to generate the astigmatic focus-error signal, the push-pull track-error signal, the sum signal for phase-change disk readout, and the differential edge-signal for mark-edge detection on various types of optical media. Commercially objectives that contain an adjustable collar for correcting a variety of substrate thickness are adopted in this testing system[*]. Thus, the spherical aberration caused by focusing through the substrates of different recording layers can be generally corrected and enables testing of disks with substrate thickness below 1.2 mm by tuning of the adjustable collars on a pair of microscope objectives in the system. In addition, A commercially available aspheric singlet, designed for operation at 0.78 um, was used for focus the incident laser beam to a slightly aberrated spot. The collar of one of the microscope objective was used to focus the re-collimated beam through the optical disk substrate, and its collar adjustment was corrected for the substrate thickness within the available range.

[*] Olympus manufactures an objective lens having an infinite conjugate ratio and a NA of 0.6 that is capable of correcting for a thickness of 0.0 – 1.2 mm.

Schematic diagram of the tester is shown in Fig. 6.4.1. A collimated diode laser beam at wavelength of 650 nm is brought to a slightly aberrated focus an aspheric singlet, passes through a corrector plate and re-collimated by a microscope objective with an adjustable collar that corrects for any spherochromatism caused by use of the singlet at wrong wavelength. The corrector plate is needed is because both the asphere and the microscope objective are designed to focus through a cover glass. The microscope objective was adjusted until the emergent beam had no spherical aberration*.

Next, the beam passed through a pair of relay lens, each being a 25-mm-diameter cemented doublet with a focal length of 75 mm. The relay lenses were arranged in the 4-*f* configuration, imaging the pupil of one microscope objective onto the other while keeping the beam collimated. The bam then passed through a second microscope objective and was brought to focus at the rear focus surface of a disk with polycarbonate substrate. In the system, the only element that moves in response to focusing and tracking signals is an aspheric singlet. [6-7]

* The emergent beam was tested with a shear plate.

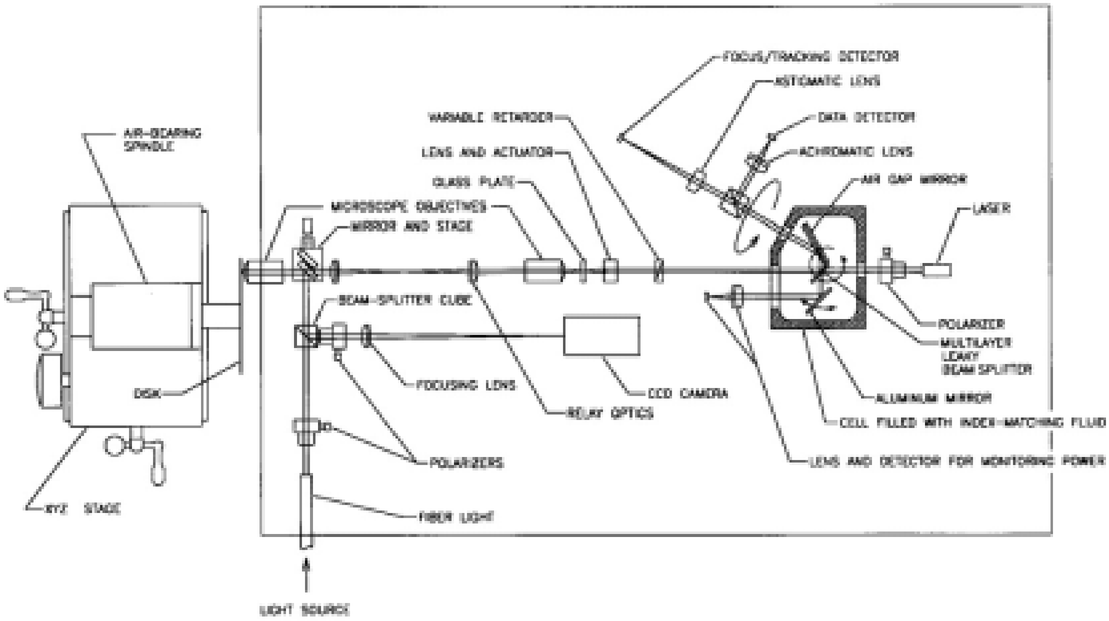


Fig. 6.4.1. Schematic diagram of the dynamic tester.

6.4.2 Dynamic Test Result

For four recording layers, single pulse writing strategies were used to write a 3T (about 0.46 um) data marks train at a constant linear speed of 8.4 m/s. The carrier-to-noise ratio (CNR) obtained from a spectrum analyzer as a function of writing power was shown in Fig. 6.4.2 at 1 mW read power. Over 40 dB signal intensity was obtained form the first recording layer. However, lower signal intensity (7 dB less) was obtained from the bottom recording layer, as shown in Fig. 6.4.3. Thus, additional preamplifiers and noise filters in the data channels were needed for balancing the signals from different recording layers. Larger signal intensity difference (8 dB less) was obtained from the recording layers if writing power was fixed at 10 mW. Therefore, further optimization of the writing power on each recording layer is needed to improve the signal qualities. In addition, the vertical depth of written marks on the first recording layer, observed by AFM and shown in

Fig. 6.4.4, was about 103nm, which in the same order of data marks in DVD-ROM (DVD-read only memory) disk.

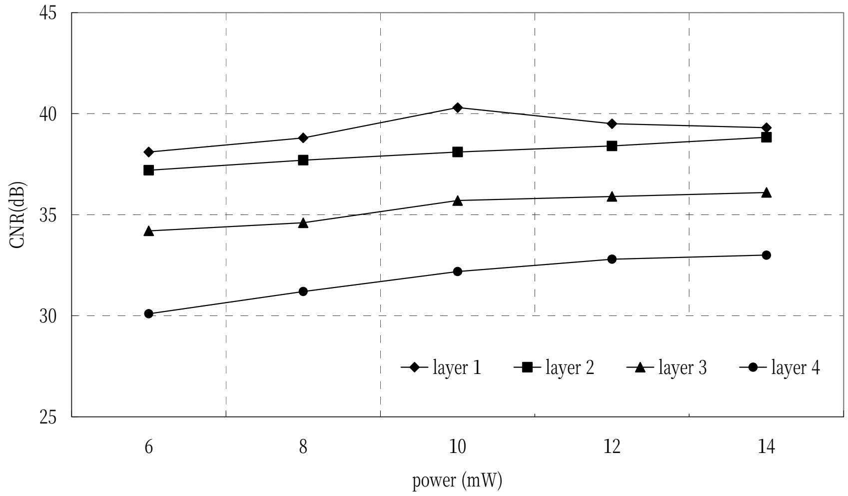


Fig. 6.4.2. Carrier to noise ratio (CNR) as a function of writing power in different recording layer.

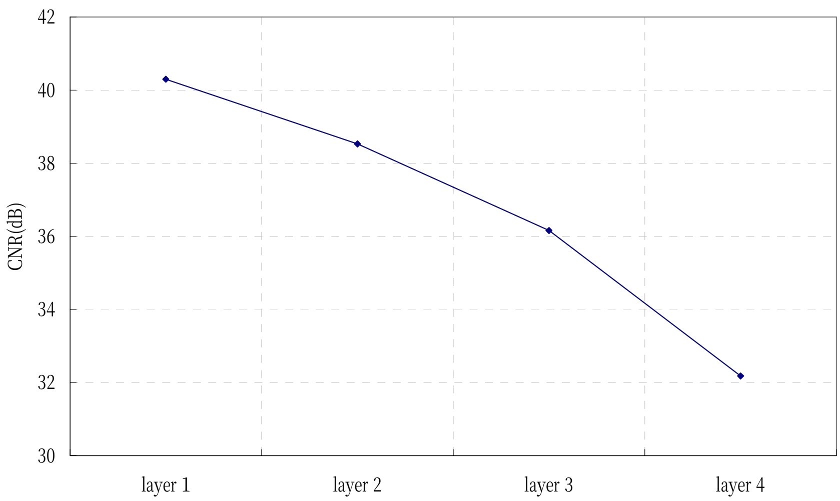


Fig. 6.4.3. CNR of recording layers at writing power of 10mW.

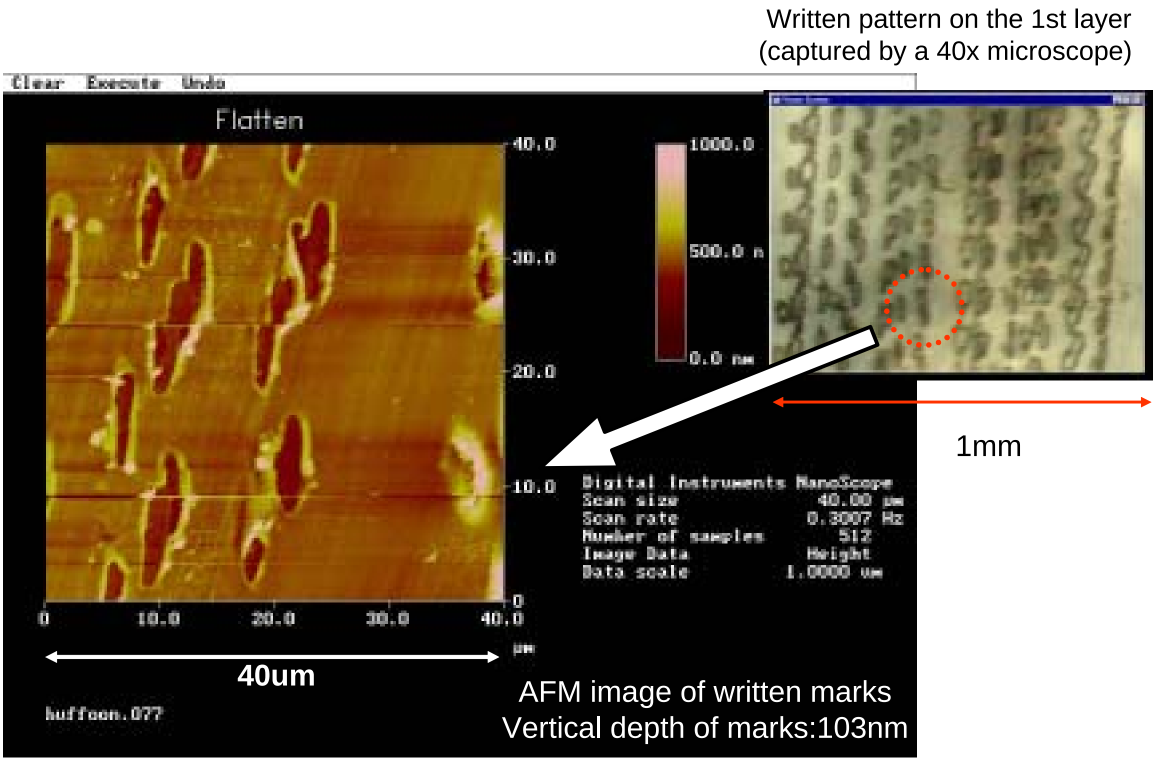
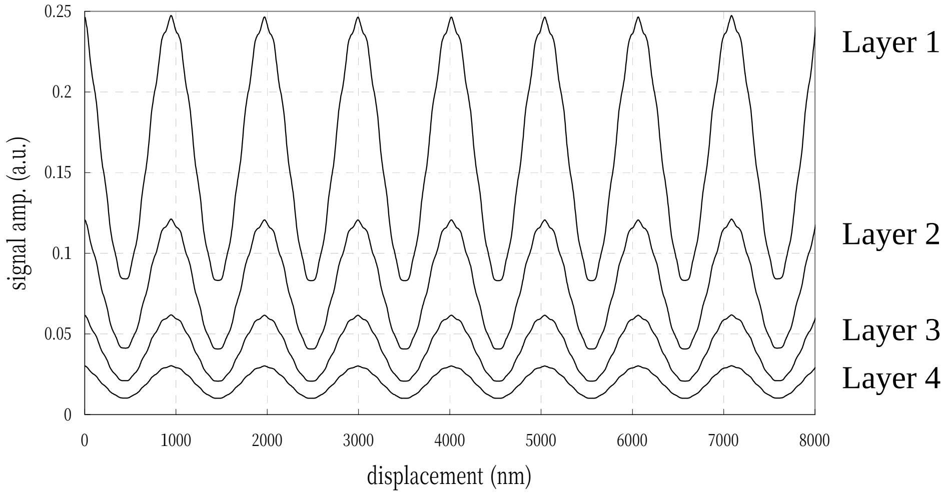


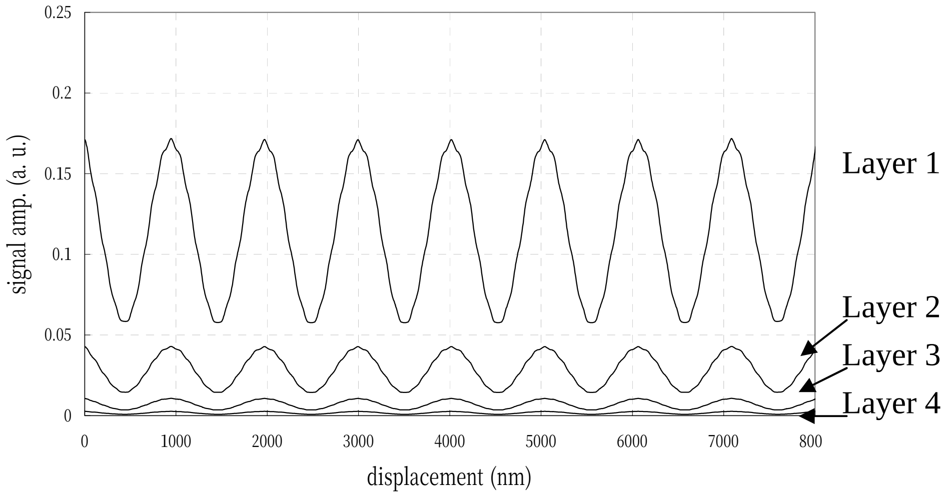
Fig 6.4.4. AFM image of the written marks on the first recording layer. Vertical depth of written marks are about 103nm.

6.4.3 Numerical Analysis of Readout Signal

The multilayer disk, shown in Fig. 6.2.3, was modeled by a commercial software, Diffract, [6-8] to simulate the readout signal form different recording layers. The optical characteristics, reflection (*R*) and transmittance (*T*), of the optical switching layer were variables. For example, if a portion of the recording layer is in the focused spot area, the *R* and *T* are 20% and 50%, respectively; otherwise, the other portion of the recording layer that is not in focus exhibits R and T of 10% and 60%, respectively [6-6]. The 3T mark train with 50% duty cycle was embedded on the recording layers. The readout signal was acquired as the focused spot was scanned. The calculated readout signals from four recording layers are shown in Fig. 6.4.5 (a). A disk without the optical switching layer was modeled as a comparison. The disk structure was similar to the previous one, but the optical switching layer was replaced by a thin metal film. The *R* and *T* were set to 10% and 60%, respectively. The calculated results, shown in Fig 6.4.5 (b), reveal extremely low signal intensity, compared to the disk-with-switching-layer calculation for the bottom recording layers. These simulation results agree well with measured data. The experiment used data marks recorded at a writing power of 10 mW. The readout signals from layer one to four at readout power of 1 mW are shown in Fig. 6.4.6. Because the presence of the upper recording layers, the readout signal amplitude form layer 4 is much lower than that from layer 1. One way to increase the CNR of the readout signal is increasing the read power for compensating the readout energy truncated by other recording layers. In addition, high transmittance recording layer design can also resolve the issue. The readout signal amplitude ratio of the layers (about 8:4:2:1) agrees with the calculated result shown in Fig. 6.4.5 (a). The results indicate the readout signals were enhanced by the optical switching layers.

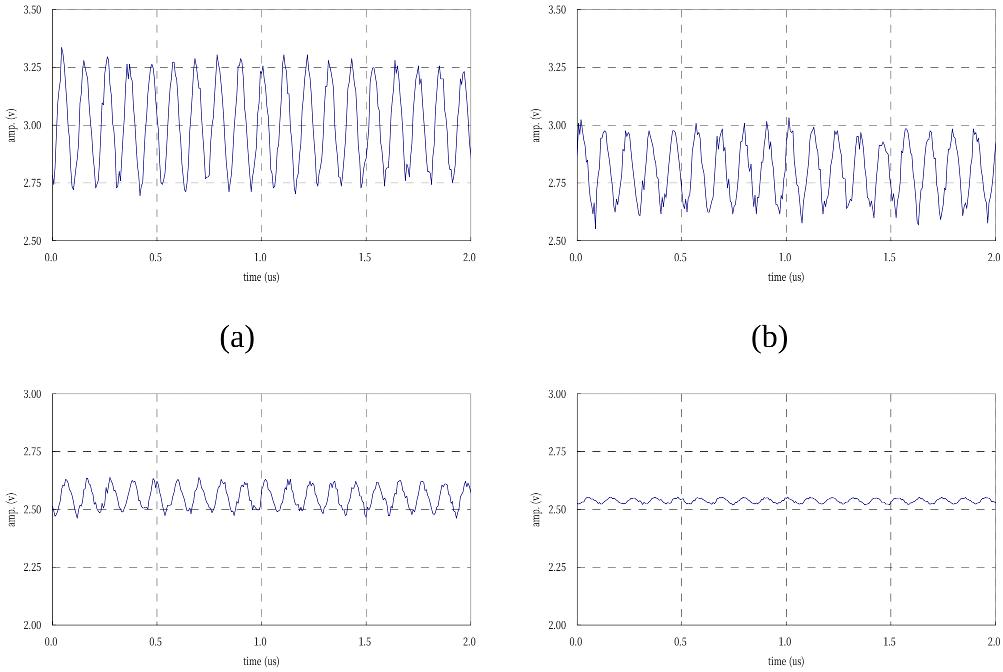


(a)



(b)

Fig. 6.4.5. Calculated readout signals from recording layers of the disk (a) with (b) without optical switching layers.



(a) (b)

(c) (d)

Fig. 6.4.6. Readout signal from recording layer (a) 1, (b) 2, (c) 3, and (d) 4.

6.5 Summary

A write-once multilayer optical disk using transparent recording materials and nonlinear optical switching layers is demonstrated and achieves large data capacity on single disk substrate. In such a disk, the optical switching layer is designed to modulate the laser energy distribution and enhance the readout signals. A four-layer recordable disk was designed and fabricated for writing/reading tests. Writing power of 10 mW was used to write 3T data marks, and a CNR of more than 32dB was obtained. Therefore, transparent recording material with an optical switching layer can be used to reduce the writing laser power and increase the number of recording layers in the volumetric disk.

CHAPTER 7

CONCLUSION

Volumetric optical storage extends the effective areal recording density and capacity per disk with a potential to increase the media capacity without significantly affecting the cost of the drives. Instead of recording only on a plane, the volumetric storage is stored in multiple planes. However, there are also limitations to the third dimension, including higher optical power requirements depending on the transparency of the material, dealing with aberrations and interlayer crosstalk while imaging through the volume, extra costs associated with focusing and tracking in three dimensions, and smaller signal levels required more complex signal processing and error correction schemes. In the dissertation, the optical switching structures in the volumetric optical data storage technologies show great potential to multiply the capacity on a disk substrate. Besides, the system and material aspects of this technology via theoretical modeling and experiments were studied.

(A) Optical Switching Structure in Rewritable Type media

In a dual-layer optical disk, the optical characteristics (R, T, A) of the top data layer affect the quantity of interlayer crosstalk and peak laser power on the bottom data layer while reading and writing, respectively. Besides, the transmittance of upper layer of a dual-layer optical disk must be sufficiently large for accessing another data layer. Therefore, adequate optical characteristics design of upper data layer is essential for a dual-layer optical disk. However, the rewritable type medium structures, such as phase change disk or magneto-optical disk, exhibiting low transmittance are not easy to design a rewritable type top layer in the dual-layer optical disk. Therefore, A temperature-dependent optical material functioned as an optical switch attached to upper recording layer is proposed to reduce laser energy loss and increase recording sensitivity for reading and recording, respectively.

The dual layer optical disk with optical switching layer was modeled. Adding a thin thermo-induced semiconductor-to-metal phase transition optical switching layer to layer 1 results in increase of the absorption and transmittance by 10 and 30% when laser beam focuses on top and bottom recording layer of a dual layer optical disk, respectively. The study reveals that the efficiency of laser power for recording by adding an optical switching layer can be easily optimized. Moreover, the contrast of reflected signal is increased by 20%.

The silver oxide sample exhibiting transmittance change by 43% with increased temperature was chosen for the optical switching layer in the disk. Experimental results showed the peak writing power could be reduced by 42% in the disk with an additional optical switching layer. Furthermore, Optical switching layer is promising for volumetric recording to optimize the writing laser power, thus R/W performance.

(B) Optical Switching Structure in Write-Once Type media

In a multilayer optical disk, laser energy is decreased by the presence of out-of-focus recording layers. The total number of recording layers is therefore limited by the fixed laser power of the pickup. An intensity-dependent nonlinear optical structure as an optical switching layer added to each recording layer was proposed to modulate the absorption and transmission of light in the recording layers, depending on whether the laser is focused on it or not. In addition, the conventional low-transmittance recording material was replaced by a transparent one (polycarbonate) to improve laser energy efficiency, suppress the interlayer crosstalk, and increase the total number of recording layers. Specifically, this simplified structure offers a three-dimensional optical disk with significantly decreased crosstalk, large number of inexpensive recording layers on a substrate, and reduced reading/recording laser power.

In the disk, an optical switching layer is adopted to reduce laser energy decay and increase recording sensitivity for reading and recording, respectively. A well-defined deformation area (mark) with submicron to nanometric dimensions can be yielded precisely on the transparent films by a focused laser beam. The peak writing power of 7 mW for a four-layer recordable medium, fabricated by molding and spin bonding techniques, was demonstrated experimentally as an example. Furthermore, a four-layer recordable disk was designed and fabricated for writing/reading tests. Writing power of 10 mW was used to write 3T data marks, and a CNR of more than 32dB was obtained. Therefore, transparent recording material with an optical switching layer can be used to reduce the writing laser power and increase the number of recording layers in the volumetric disks.

(C) Future Work

(1) Develop New Material for Optical Switching Structure

Additional works are required to improve the performance of a volumetric optical data storage device in both system and material aspects. Suggestion for future work is to develop next generation triple-layer silver oxide structure material. It is clear that the transmission rate and nonlinear coefficient of current triple-layer silver oxide structure limits the maximum surface density. The next generation triple-layer silver oxide structure should have transmission rate of higher than 95%.

(2) Parallel Access

With the strong demand for capacity for removable systems comes an equally strong demand for high data rates. The conventional method to increase data rates in a disk system is to increase the rotation speed and to increase the linear bit density. Present data transfer rates are limited by rotational speed of spindle motor and servo speeds. To achieve a high data transfer rate, a multiple beam optical system is proposed. The motivation is the need of individually-addressable multiple-beam sources for simultaneous recording on multiple layers and adjustability of individual spot spacing on the recording layers of the disk. For example, laser and detector arrays to access data in parallel from a multilayer disk as shown in Fig. 7.1. Multiple beams with different light path are generated by laser diodes array and shaped to collimate light. After passing a beam splitter and wave plates, the beam hits a diffractive optical element (DOE) and objective optics. The beams illuminate separate recording layers and reflect back to data and servo detectors. In this system, laser diode array and DOE are the key factors in multilayer parallel recording. However, issues such as heat accumulation on laser diode array, multi-beam placement error, and circuit complexity are needed to overcome.

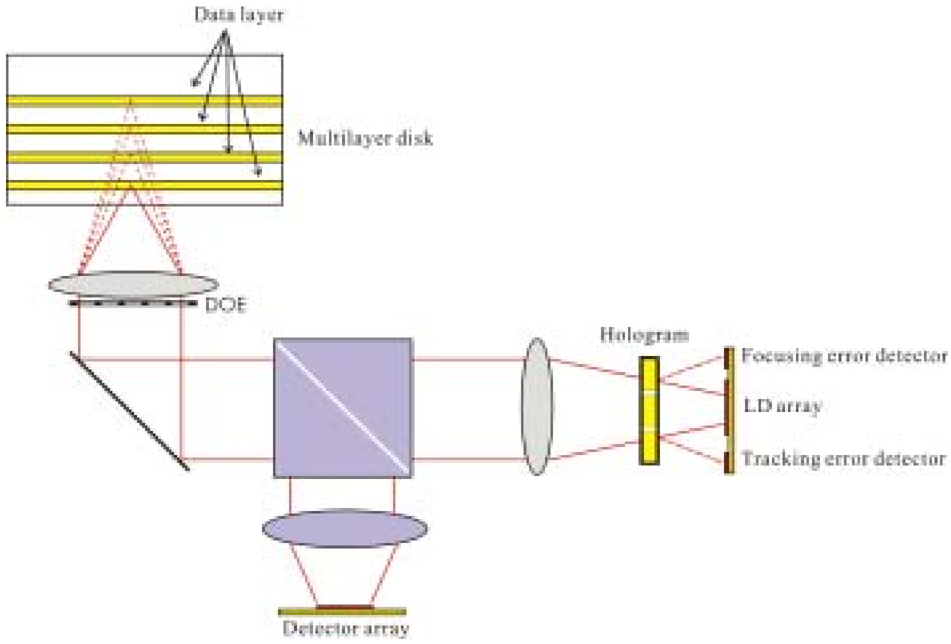


Fig. 7.1. Schematic diagram of multi-beam optical head accessing a multilayer disk.

Conventional lenses and their mounting with substantial mass limit fast access motion. Based on the advantages of low weight and high flexibility, a hard-disk-like pickup head using VCSEL (vertical cavity surface emitting laser) and MOEMS (micro opto-electro-mechanical system) array for parallel recording on multilayer disk is proposed for further access speed improvement. This idea involves the use of VCSEL arrays flying directly above an optical disk and microclines array controlling the light intensity distribution on recording layers using a near field geometry and MOEMS techniques, respectively. In the system, the laser is used to both record and detect the presence of a bit based on the optical signal that is fed back into the laser. In order to achieve high data rates, massively parallel access through VCSEL array is contemplated, as shown in Fig. 7.2.

For the longer term and significant gain in market share, removable volumetric parallel accessible storage systems approaches appear attractive. The key issue for volumetric storage is the development of an inexpensive, reliable write-once material. These technologies are especially important since they can drive the low-cost manufacturing of optoelectronic and MOEMS device arrays that can be critical for many applications.

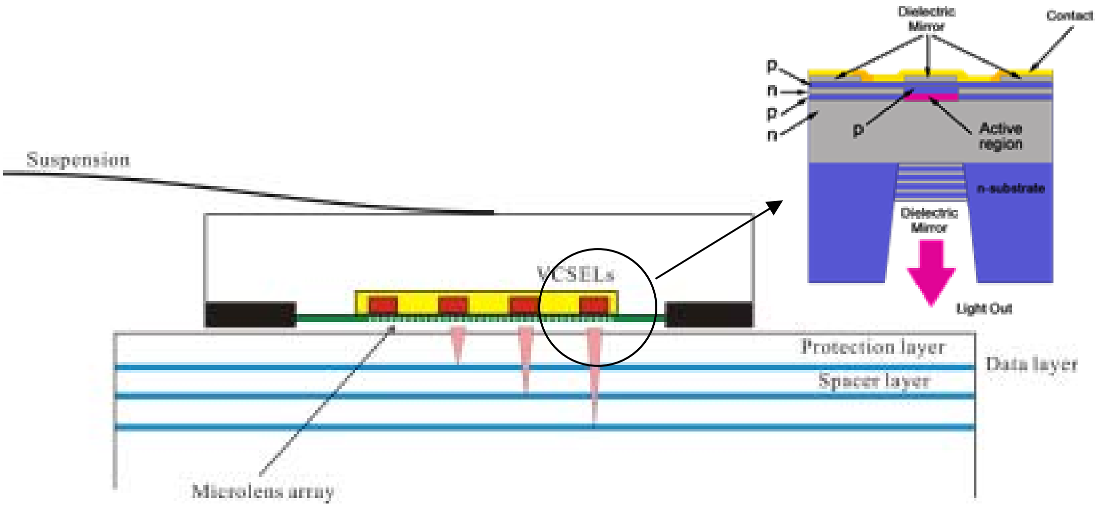


Fig. 7.2. Schematic diagram of a VCSEL array access with massively parallel optics architecture to optical disks for faster data transfer rate.

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Patent

1.**Fung-Hsu Wu** and Han-Ping David Shieh, "A Novel Optical Switching for Volumetric Optical Disks," Taiwan Patent pending.
2.**Fung-Hsu Wu** and Han-Ping David Shieh, "A Novel Write-Once Multi-layer Optical Disk using Transparent Recordable Material with Optical Switching Layer," Taiwan Patent pending

Vita

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Experience

Sep. 02’ – Mar. 03’: Visiting scholar at The Optical Sciences Center,
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