Chapter 1

Introduction

1.1 Introduction

The principles of optical data storage, including read-only memory (ROM), write-once read-many (WORM) and rewritable system, is presented in this chapter. After a short overview, some critical issues regarding light path and optical pickup are considered. Next, the free-space micro-opto-electro-mechanical (MOEMS) techniques for reducing the size of the optical pickup and the overall form factor of the drive are introduced. Finally, the motivation and organization of this thesis are discussed.

1.2 Optical data storage

Since audio compact disk was introduced in 1983, significant advances have been made in read-only optical storage technology, such as compact disk read only memory-read only memory (CD-ROM), versatile compact disk/disc (VCD), digital versatile disc-video (DVD-Video), and digital versatile disc-read only memory (DVD-ROM) [1, 2]. Read-only optical disks have the advantages of removability, low production cost, non-contact data retrieval. Therefore, read-only optical disks have been widely used for distributing video data, software, databases, catalogues, and have become the most popular multi-media. The disadvantage, however, is that users can not rewrite or update the data on the disk.

To record data on optical disks, two kinds of recordable disks have been developed: (1) Write-Once Read-Many (WORM) disks that can be written only once, and (2) Rewritable disks that can be written plurality of times.

Compact Disk Recordable (CD-R) and Digital Versatile Disk Recording (DVD-R) belong to the family of WORM recording. They are used to store unalterable information, such as data backup, medical record, large archive databases, and medical records. However, the write-once media are inconvenient for the users who need to rewrite the stored files.

Compact Disk Rewritable (CD-RW) and Digital Versatile Disk Rewritable (DVD-RW) are erasable media which can be written over many times. Thus, these media can be used as peripheral data storage devices of computers, and applications in the video and entertainment. In addition, erasable optical disks possess the advantage of portability, high capacity, and long lifetime. Therefore, erasable optical disks are convenient storage option in information processing, communication, and multi-media applications.

Two major rewritable disks are Magneto-optical (MO) disks and Phase Change (PC) disks. The magnetization of MO recording materials, such as TbFeCo, can be changed by applying a focused laser beam and an external magnetic field simultaneously. When the laser heats the media to the Curie point (about 200 ℃), the magnetic dipole in the medium becomes unstable. By applying an external magnetic field, the marks can be written. Recorded signals can be detected by the polarization alteration of the reflected light due to Kerr effect. In contrast, the phase change recording operates on the principle that the reflectivity of phase change media, such as GeTeSb, are different for its the amorphous and crystalline states. Before writing data on the disk for the first time, the disk needs to be initialized to the ordered, crystalline state as the background. In the writing process, an intense laser pulse is applied to melt the material and quench it into the amorphous phase as the recording marks. For erasing, a longer-period, lower-power laser beam is used to anneal the material into the crystallized phase. Both MO and PC media require special designs to write, read, and erase information in the recording layer.

1.3 Design issues in light path and pickup system

1.3.1 Media substrate

The minimum size of recorded mark of DVD is about 1.0 μm^2 [3], which is much smaller than the sizes of the dust of the airborne contaminations. Two distinct situations may occur without additional protection. One is scratches or fingerprint perturbing the incident wave front (phase error), and the other is large dust particle obscuring the incident beam (amplitude attenuation). The protection layer of disk is placed above the recording layer of the disk to protect the recorded mark from damages, such as large particle, scratches and fingerprints shown in Fig. 1- 1.

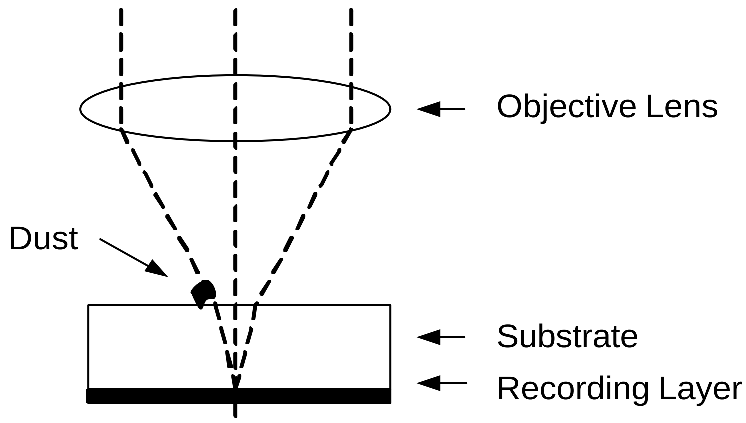


Fig. 1- 1 Separation of the recording layer from environment effects

Moreover, the comatic aberration of readout spot is proportional to t NA^3 [4], where t is the thickness of the protection layer and NA is the numerical number of objective lens. The comatic aberration can be reduced with a thin protection layer. However, the thickness of the protection layer should not be too thin for mechanical rigidity.

For example of CD-type storage, the substrate thickness should be 1.2 mm. 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. For HD DVD, a cover layer of 0.1 mm is used as protection layer.

1.3.2 Optical path in rewritable system

The elements in the optical pickup head, such as lens, prisms, and mirrors, are designed to direct light from the laser diode onto the optical disk. A detector is used for retrieving the recorded data on the disk. Optical system of two types of rewritable media (PC and MO) will be discussed in this section.

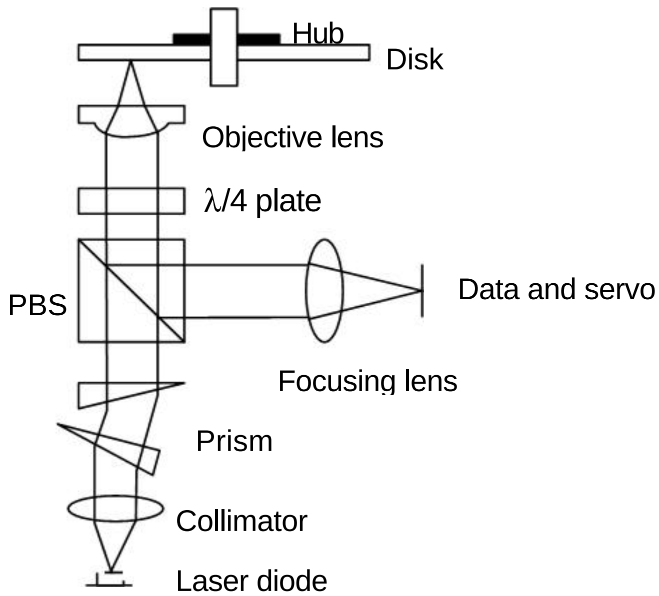


Fig. 1- 2 Optical system for phase change (PC) storage system

The optical system for PC system is shown in Fig. 1- 2. Since the thickness of the active region in a laser diode is only a fraction of a micrometer, diffraction effects cause the emerging beam to diverge rapidly. In practical applications of laser diodes, the diverging beam of laser diode is collimated by a collimator. The emerging beam has different dimensions in the direction parallel and perpendicular to the laser diode junction. The beam shape on the collimator is therefore elliptical with the major axis (long axis) perpendicular to the diode junction. After passing the collimating lens, the beam becomes parallel but remains elliptical. A pair of prism is then used to make the beam with a circular shape. The bending of the beam on the prism surface changes its diameter in the plane of incident, but leaves the diameter in the perpendicular direction intact. In optical recording, the diameter of collimated beam is matched to that of the objective, thus eliminating the need of beam expander.

For the three-beam tracking, a beam splitter is inserted between the beam shaper and the polarizing beam splitter (PBS) to generate three spots in the far field for tracking purpose. The most commonly used beam splitting device is grating. The PBS and the quarter-wave plate make an optical circulator. The optical circulator passes all of the linearly polarized light from the laser diode to the disk and redirects all the reflected light to the data and servo detectors. The collimated and reshaped beam of the laser diode is focused on the disk surface by an objective lens. The objective lens is designed to be aberration-free, so the focused spot is as minima as possible but subject to diffractive spreading.

In MO recording shown in Fig. 1- 3, a leaky polarizing beam splitter (LPBS) with adjustable leakage ratio is used instead of a PBS. About 70 to 80 % of the linearly polarized light from the laser diode passes through the LPBS. The linearly polarized light is the combination of two polarization state, namely right-state and left-state. The linearly polarized light is rotated according to the direction of magnetization in the recording media known as Kerr effect shown in Fig. 1- 4 (a). The LPBS redirects the beam with its polarization to the data detector. The state of polarization of laser beam after passing LPBS twice is similar to the state before (Fig. 1- 3(b)). After passing through a half-wave plate, the rotation of reflected light changes to an amount of 45°(Fig. 1- 4 (c)). A Wollaston prism and two detectors are then used to provide a differential signal for signal processing. The Wollaston prism separates the two orthogonal polarized beams due to its birefringence.

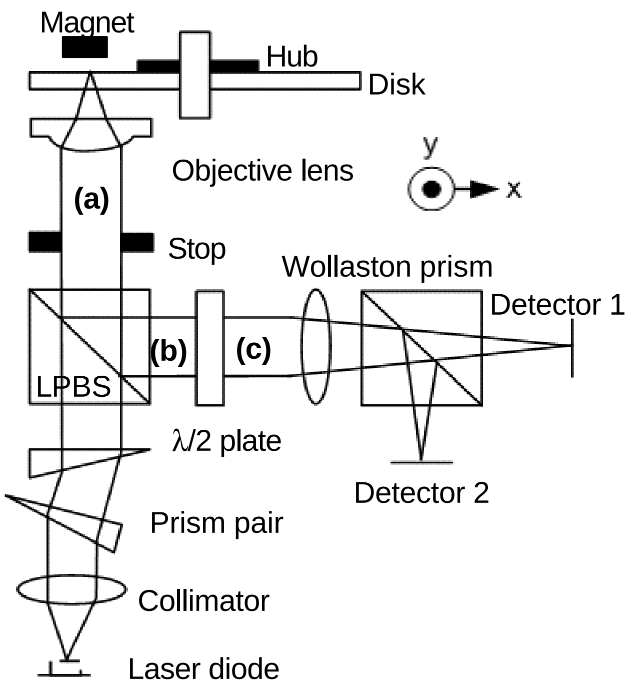


Fig. 1- 3 Optical system for magneto-optical (MO) storage system

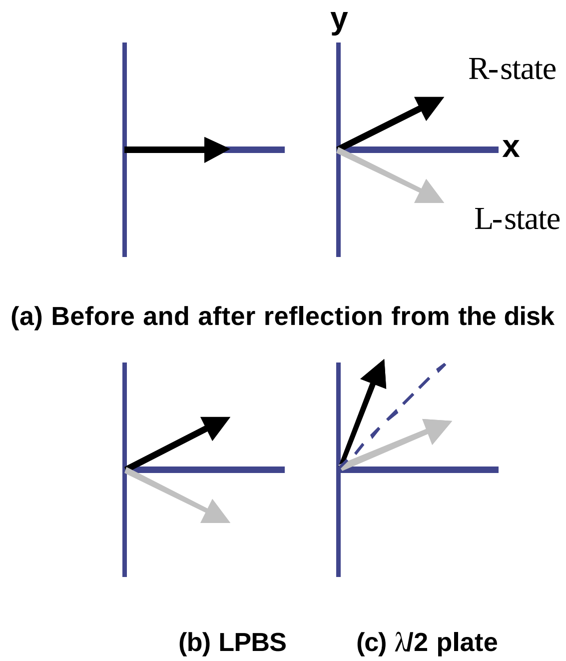
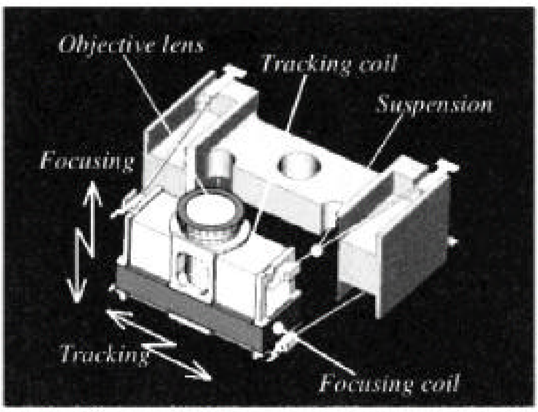


Fig. 1- 4 Polarization of (a) before and after reflection from the disk (b) after reflection from LPBS (c) after passing through λ/2 plate

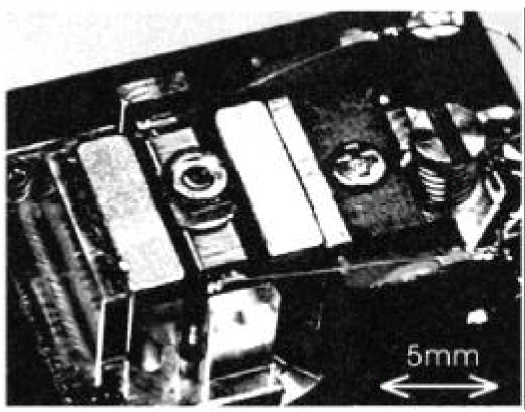
1.3.3 Tracking and focusing servo

In order to assure a uniformly intense signal and free of cross-talk, the mechanical components are needed to keep the optical pickup stylus centered on the data track. The tracking tolerance for CD-ROM is typically ± 0.1 μm. The depth of focus of the optical stylus is as small as ± 0.5 μm [5]. During Read/Write/Erase operations, the height and position of objective must be maintained with high accuracy. Therefore, an active servo-system is essential for keeping the optical stylus within submicron tracking and focus tolerances.

In practice, the objective lens which is controlled by the voice-coil actuator will move back and forth to retain its distance within a suitable range from the disk. In this case, the voice-coil uses electric current to generate magnetic field and magnetic force to drive the objective lens. In order to support enough force, the mechanical structures are usually massive. The schematic diagram and photograph of a miniature actuator are shown in Fig. 1- 5. A focus coil is located at the bottom of the actuator to work as a balancing mass which ensures the alignment of the driving force and the center of gravity. For an example, the total movable part with a weight of 175 mg and the size of 7.8 mm   3.2 mm   6.4 mm were achieved [6].



(a) Schematic diagram



(b) photograph

Fig. 1- 5 (a) Schematic diagram and (b) photograph of miniature actuator

The weight of optical devices greatly affects the focusing servo and tracking servo. Generally, resonance frequency (f) of an actuator is determined by the following equation where m and k denote the weight of movable part and the elasticity, respectively.

$$f = \sqrt{\frac{k}{m}} \qquad \text{(Eq. 1-1)}$$

A high bandwidth servo system can be achieved by means of downsizing the actuator and its weight.

1.4 The development of pickup head miniaturization

Issues of future pickup improvement include miniaturization, integration, and parallel processing (multi beams). These devices are expected to reduce the cost, size, and weight of opto-mechanical structure, making the device more competitive in terms of price and performance.

Sony and NEC proposed a holographic optical element (HOE) that performs all beam splitting functions. This is the first step towards the compact design [7, 8]. The laser diode grating units as described by Ophey from Philips [9] and marketed by Sharp [10] is the next practical step in optical pickup miniaturization. There are several benefits to put the laser module, beam splitter, and detector array into a single package. The units mentioned above are already produced commercially, particular in read-only pickups for CD players.

1.4.1 Micro-opto-electric-mechanical-system (MOEMS) technology

The uses of integrated optics mentioned above have suffered from high coupling loss in and out of waveguides, thus raising the overall laser power budget. Until now, as the tremendous improvement on semiconductor electronics, many efforts have been made on the integration of electronics, mechanics, and optics and eventually lead to Micro-opto-electric-mechanical-systems (MOEMS) technique.

1.4.2 Waveguides and holographic (diffractive) components

For the waveguide approach, S. Ura *et al.* employed a focusing grating coupler (FGC) as a pickup in record/read mechanism [11]. A FGC is a kind of diffractive waveguide. It has chirped and curved grating pattern to couple a guided wave from laser diode to focus in the free space [12-14], as shown in Fig. 1- 3. The error signals are also required for the automatic servo operation. The focusing and tracking error detections are based on the Foucault and push-pull methods respectively, which are modified for the implementation of diffractive components in a waveguide.

The 3dB focus spot width of FGC was measured to be approximately 2 μm, while the theoretical diffraction-limited value is 1.4 μm [5]. Major aberrations introduced by the fabrication errors are astigmatism and coma, which cause the deterioration of the focused spot. Since holographic optical elements (HOE) are highly dispersive, the wavelength deviation is also an issue in the optical design and fabrication accuracy.

The fabrication accuracy required to obtain the diffraction-limited focused spot becomes stringent with increasing NA of the focusing grating. For example, the maximum tolerance of linear dimension and wavelength deviation in FGC with a NA of 0.24 are estimated to be ±0.6% and ±0.9% respectively, while a NA of 0.45requests ±0.09% and ±0.1% respectively [12-14].

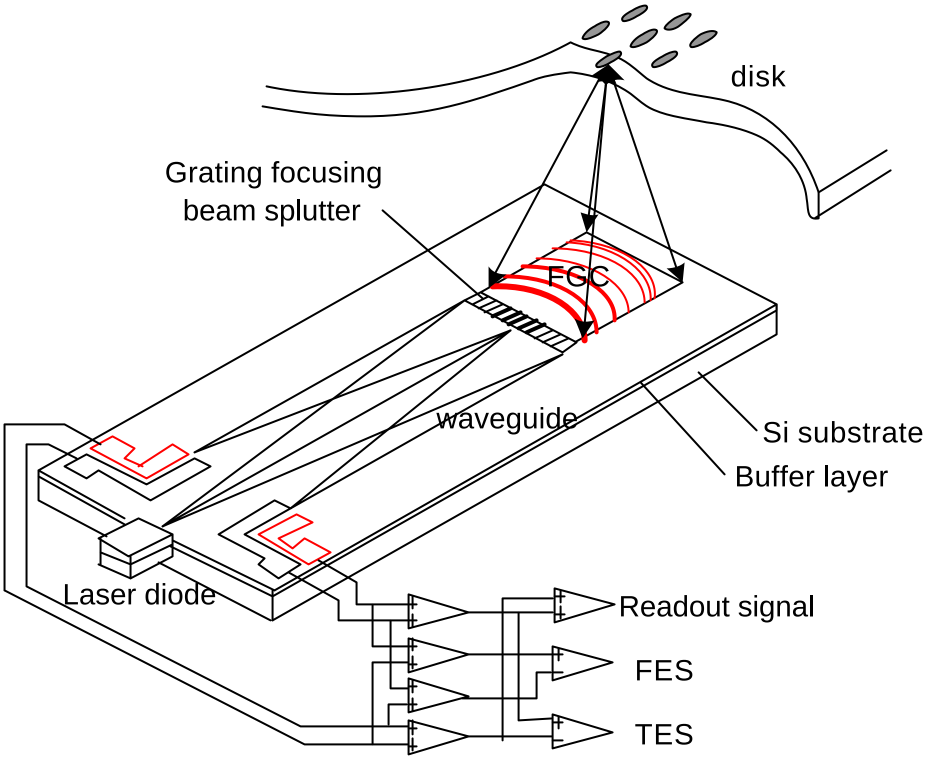
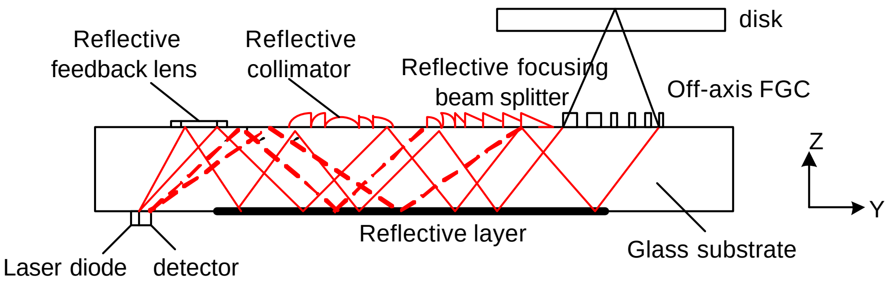


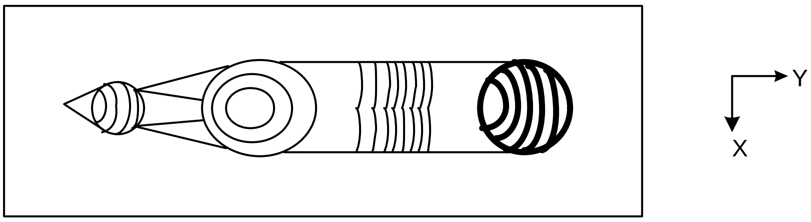
Fig. 1- 6 Schematic of the integrated optic disk pickup (IODPU). The curved and chirped grating incorporates the input/output coupling and the focusing by the wavefront conversion based on holographic principle [12-14]

1.4.3 Planar pickup based on glass substrate light guide

The use of diffractive optical elements (DOEs) to replace individual refractive optics is a promising development. T. Shiono *et al*. employed planar optics integrated with various diffractive structures on a glass substrate [15]. The glass substrate is used as a light guide in which the beam follows a zigzag optical path, as shown in Fig. 1- 7. With this approach, the beam hits those diffractive elements in sequence. The focusing and tracking error detections are based on the Foucault and push-pull methods respectively, which are achieved by the off-axis blazed structure called reflection-twin-focusing beam splitter.



(a)



(b)

Fig. 1- 7 Schematic of the planar optical disk pickup based on glass-substrate based: (a) side view, (b) plane figure

The focused spot in full width at half maximum (FWHM) is about 1.0 μm at λ = 0.63 μm. This value is very close to the diffraction-limited (0.98 μm). Theoretical efficiency of the system was about 46 %, with reflection loss neglected at each interface. This approach requires precision alignment on both sides of the substrate.

Tab. 1- 1 Pros and Cons of the integrated optic disk pickup (IODPU) device

Pros	**Cons**
Waveguide with focusing grating [11]	
1. Good integration	1. High coupling loss 2. Difficult implementation of high NA lens by the focusing grating
Diffractive optical element (DOE) planar approach [16]	
1. High coupling efficiency 2. High performance in planar micro-optical components	1. Requirement of precise alignment on both sides of the substrate

1.4.4 Free-space three dimensional micro pickup

Micromachining technology opens up many new opportunities for optical and optoelectronic applications. Micromachining technology offers unprecedented capabilities of extending the functionality and reducing the dimension of optical devices and systems. Movable structures, micro actuators, and micro-optical elements can be integrated on the same substrate using batch processing technology. By using this technique, the volume of pickup head can be reduced, thus achieving high servo bandwidth. Production cost can also be cut down with batch fabrication processes.

The MEMS-type optical pickup was first demonstrated by Lin et al in 1996 [16]. The schematic configuration based on the free-space micro-optical bench is shown in Fig. 1- 8. The entire free-space optical system which consists of a self-aligned edge-emitting semiconductor laser diode, collimating and focusing lenses, a beam splitter, and a 45° mirrors can be integrated on a silicon substrate.

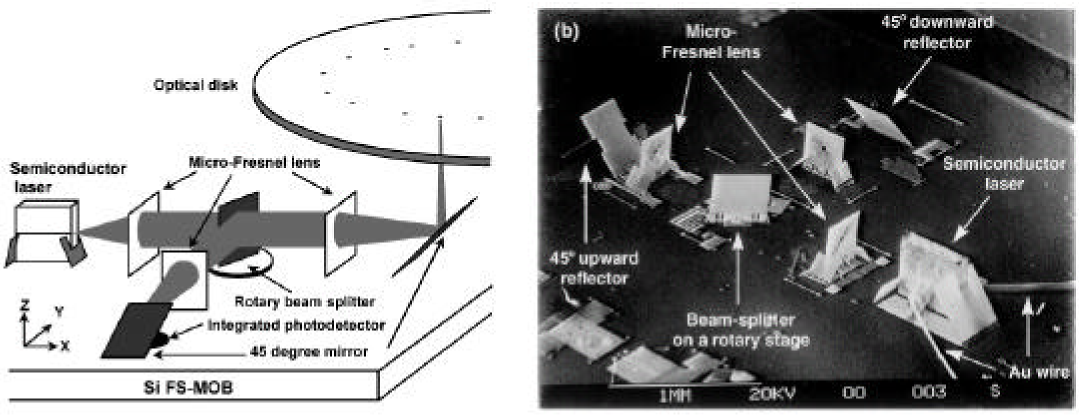


Fig. 1- 8 (a) Schematic and (b) scanning electron micrograph of free-space integrated optical head.

The system was designed for ? = 980 nm. The optical axis was 258 µm above the substrate surface. The diameter of each element was 250 µm. The components were made of 2-µm-thick polysilicon. To accommodate the Multi-User MEMS Process

(MUMPs), Fresnel zone plates were used as the collimator and focusing lenses. However, the low NA (~ 0.17) of the objective lens and 980-nm wavelength dose not fit the DVD specification. Therefore, a MEMS-type DVD-like pickup (for 650 nm wavelength and 0.1 mm cover layer) were proposed and shown in Fig. 1- 9. The system consists of a collimator and a beam shaper, a beam splitter, a polarizing beam splitter, a quarter-wave retarder, mirrors and an objective lens. All the optical elements have been prealigned during the fabrication stages. The light emitted form the laser diode is first collimated by a Fresnel lens. The light then passes through the beam splitter to generate three spots for three-beam tracking. To adjust the energy distribution among the three beams, diffractive devices such as fan-out elements are employed. Light then passes through the polarizing beam splitter (PBS) made of a sub-wavelength grating. The light will be reflected upward by the 45° mirror, and then focused on the disk by a harmonic objective lens [17]. The returned light is collimated by the same objective lens (micro refractive lens or diffractive lens) and focused onto the detector.

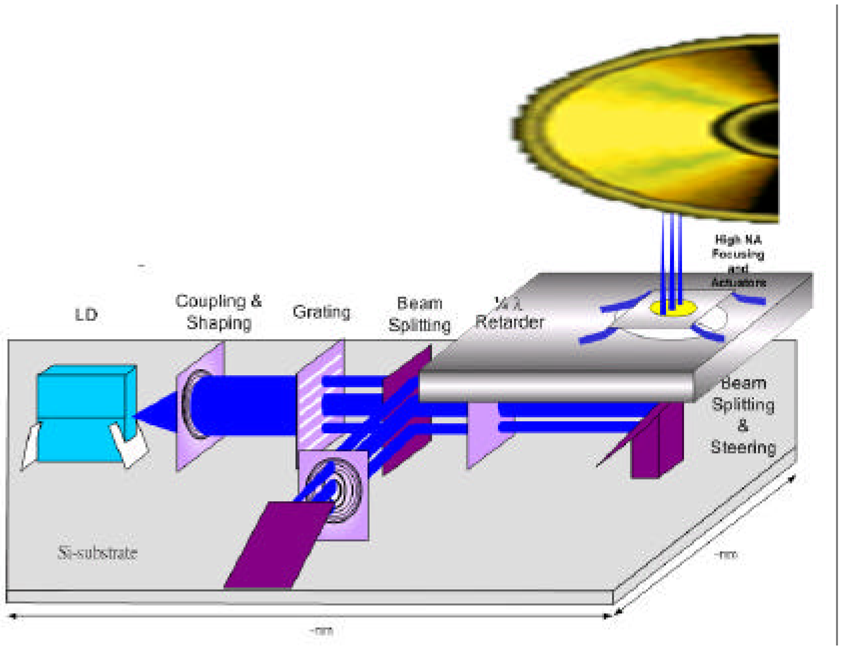


Fig. 1- 9 Schematic representation of the proposed MEMS-type DVD Pickup

1.5 Objective

The objective lens is the key device in the optical system of the pickup head which determines the performance and radius of the focused spot. The objective of this thesis is to design an objective lens for a MEMS-type DVD-like optical head at 650 nm wavelength, for a disk with 0.1 μm cover layer. In order to achieve a high NA of 0.6, and a small-size objective lens, two MEMS-type optical configurations (diffractive and refractive) are proposed and evaluated individually. The target size of the objective lens is in the range of 1 mm^3.

1.6 Organization of this thesis

The thesis includes the following chapters. Chapter 1 introduces the current status of optical storage technology and the motivation and the objective of this thesis. The fundamental optics for DVD pickup will be described in Chapter 2. Chapter 3 reviews the DVD specification and MEMS processes that will be used for the fabrication of the proposed optical pickup. Refractive lenses and diffractive lens are discussed in Chapters 4 and 5, respectively. In these two chapters, the simulation results will be shown. Finally, a conclusion is in Chapter 6.