Chapter 3: Information Storage with Optics

DIGITAL INFORMATION STORAGE

Energy and mass are the fundamental physical quantities. Time and space are the fundamental physical dimensions. The pattern of the distribution of energy over time or space generates information.

By this definition, any object continuously generates new information. Energy is transmitted from a source and finally is detected by a detector. The transmitted energy of desired information is known as *the signal*. The detected energy from unwanted information is called *noise*.

Information storage involves a medium that stores the spatial energy pattern at a given time, and represents the stored pattern at a later time.

A spatial energy pattern can always be converted into a temporal pattern by a scanning process.

Optical storage is the medium that is able to store the pattern of light intensity.

As mentioned above, information is a pattern of fluctuating energy. The signal is the desired information that propagates from one site to another and, therefore, is dynamic. However, data, which is the formatted information, is static.

If the fluctuation of the energy is measured continuously and is represented by a real number, it is an analog signal. On the contrary, if it is measured in a discrete way and is represented by an integer, it is a digital signal. In other words, a digital signal is sampled and quantized.

In the context of optical information processing and storage, energy is in the form of light intensity and the detector is a photodetector that converts light intensity into an electric signal.

The resolving power for a given position is determined by the pixel size of the detector, while the resolving power for intensity is determined by the sensitivity of the detector.

Any analog signal is indeed converted into a digital signal because it is unavoidably sampled and quantized by the detector.

A digital signal is not the quantized signal but the binarized signal. Quantized values are represented by integers such as 0,1,2,3,...; however, binarized values are represented by binary numbers; i.e., 0 and 1 only.

Binary numbers use a base of 2 while decimal numbers use a base of 10. For example, decimal 1 is 1 in binary, 2 is 10, 3 is 11, 4 is 100, 5 is 101, etc. The length of a binary number is represented in bits, which stands for a binary unit. Thus, 1 is one bit, 10 and 11 are two bits, 100 and 101 are three bits, etc.

Since there are only two states, 0 or 1, for binary data, it is easy to restore the distorted binary data to the correct data by applying a threshold at 0.5.

Provided that information is stored in a binary form in optical storage, the amount of stored information can be represented in bits. For illustration, if a tiny photographic film can store just a picture of a checkerboard with 64 black-and-white squares, the storage capacity is 64 bits.

UPPER LIMIT OF OPTICAL STORAGE DENSITY

It is well known from diffraction theory that a lens can focus light to a spot that is limited by the diffraction. This spot is sometimes called an Airy disk, which has a central bright spot surrounded with ring fringes.

The diameter of the central bright spot of the Airy disk is

$$Q = 2.44 \frac{f}{D} \lambda, \qquad \ldots\ldots \ 1$$

where f and D are the focal length and the diameter of the lens, and λ, is the wavelength of light.

In practice, one may take an approximation

$$Q \approx \lambda. \quad \text{…..} \; 2$$

For further simplification, one may consider that an area of λ^2 is required to store a bit optically. Thus, the upper limit of storage capacity for a 2-D medium is

$$SC_{2D} = \frac{\text{Area}}{\lambda^2}. \quad \text{….} \; 3$$

By considering the third dimension, one may similarly infer that a volume of λ^3 is required to store a bit in a bulk optical memory, and the upper limit of the storage capacity for 3-D medium becomes

$$SC_{3D} = \frac{\text{Volume}}{\lambda^3}. \quad \text{…..} \; 4$$

Instead of an image, we may alternatively record its Fourier-transform hologram as the memory. The original image would appear when the hologram is illuminated with the same reference beam as it was recorded.

A hologram has a total area of *a x a*, and the size of its smallest element is λ x λ.

The image is holographically formed by a Fourier-transform lens. Recalling Fourier analysis, the smallest element λ x λ will determine the size of the image that is proportional to 1/ λ x 1/ λ, and the size of the hologram *a x a* will determine the size of the smallest element of the image, which is proportional to *1/a x 1/a*.

Correspondingly, the storage capacity of a hologram is

$$SC_H = \frac{a^2}{\lambda^2}. \quad \text{……} \; 5$$

The storage capacity of the image is

$$SC_I = \frac{1/\lambda^2}{1/a^2} = \frac{a^2}{\lambda^2}. \quad \text{……} \; 6$$

The storage density of 2-D medium is the same; that is, $1/\lambda^2$, regardless of whether there is a direct bit pattern or a hologram.

When a bulk holographic medium is used to make a volume hologram, it can be multiplexed by *n* holograms. The maximum multiplexing is

$$n_{\max} = \frac{d}{\lambda}, \qquad \ldots\ldots\ 7$$

where *d* is the thickness of the volume hologram. By combining Eqs. (5) and (7), the storage capacity of a volume hologram can be calculated as follows:

$$SC_{VH} = \frac{a^2/\lambda^2}{d/\lambda} = \frac{\text{Volume}}{\lambda^3}. \qquad \ldots\ldots\ 8$$

Referring to Eqs. (8) and (4), the upper limit of the storage density for a 3-D medium is $1/\lambda^3$ regardless of whether we record directly the bit pattern plane by plane in the 3-D storage or we record and multiplex each individual volume hologram.

OPTICAL STORAGE MEDIA

1. Photographic film
2. Photopolymers
3. Photoresists
4. Thermoplastic film
5. Photorefractive materials
6. Photochromic materials
7. Magneto-Optic materials
8. Phase-Change materials

BIT-PATTERN OPTICAL STORAGE

The information is 1-D, which is related to electronic information processing systems such as computers and other communication equipment.

This 1-D information is formatted in 2-D or 3-D in an optical storage system in order to achieve the maximum storage density allowed.

The method for storing the optical information represented by a bit pattern is to record the bit pattern directly.

OPTICAL DISK

The most successful optical storage medium is the optical disk.

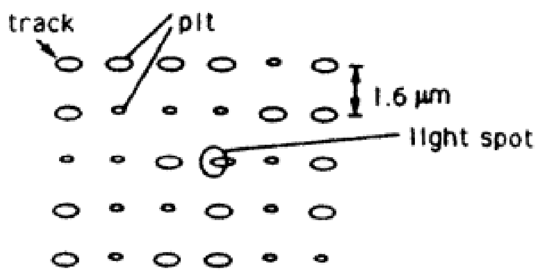

Fig. 1. Basic structure of an optical disk.

Figure 1 shows the basic structure of an optical disk.

The recorded signal is encoded in the length of the pit and the spacing of pits along the track.

The distance between two adjacent tracks (track pitch) is 1.6 µm.

The width of a pit is equal to a recording spot size of 0.5 to 0.7 µm.

The light source used in an optical disk system is usually a GaAlAs semiconductor laser diode emitting at a wavelength of 0.78 to 0.83 µm.

The spot size of the readout beam is determined by the numerical aperture (NA) of the objective lens. Typically, $\lambda/NA = 1.55$ is chosen, so the effective diameter of the readout spot is approximately 1 µm. The spot size is larger than the width of a pit, but a single readout spot does not cover two tracks.

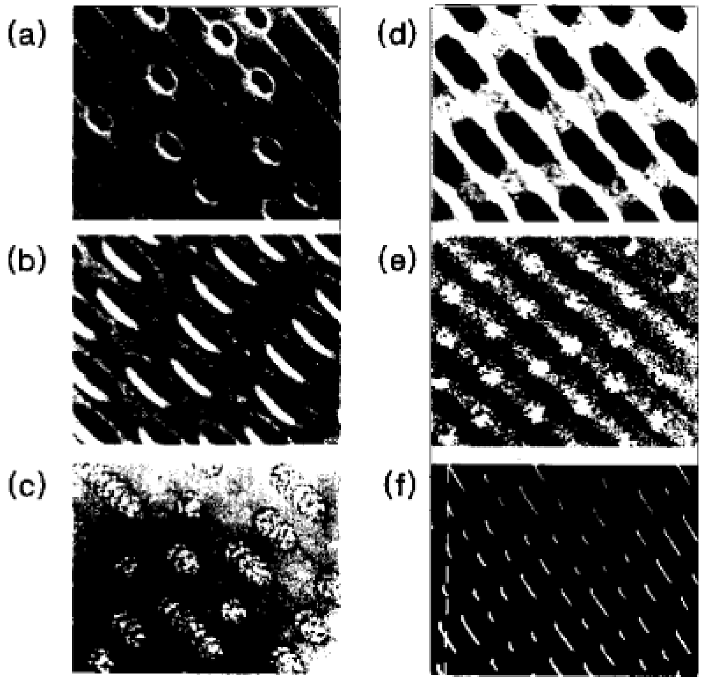

Fig. 2. Micrographs of several types of optical storage media. The tracks are straight and narrow with a 1.6 μm pitch, and are diagonally oriented in each frame.

(a) Ablative, write-once tellurium alloy.

(b) Ablative, write-once organic dye.

(c) Amorphous-to-crystalline, write-once phase-change alloy GaSb.

(d) Erasable, amorphous magneto-optic alloy GdTbFe.

(e) Erasable, crystalline-to-amorphous phase-change tellurium alloy.

(f) Read-only CD-Audio, injection-molded from poly-carbonate with a nickel stamper.

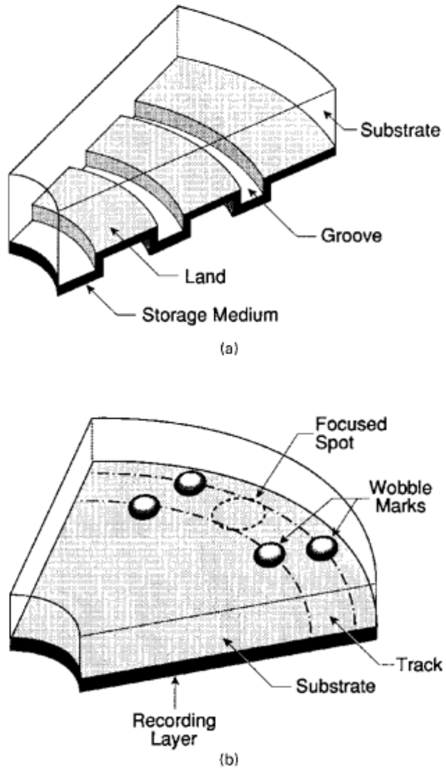

FIG. 3. (a) Lands and grooves in an optical disk. The substrate is transparent, and the laser beam must pass through it before reaching the storage medium. (b) Sampled-servo marks in an optical disk. These marks which are offset from the track center provide information regarding the position of focused spot.

1. Read-Only Memory (ROM) Optical Disk

For a read-only optical disk, such as a compact disk for music recording (CD) or a read-only memory compact disk for computers (CD-ROM), the recorded data cannot be changed after the disk is manufactured. The process of optical pickup is as follows:

When there is no pit, the light will be fully reflected to the detector. When there is a pit, the focused beam will cover both pit and the surrounding land. Both pit and land are coated with high- reflectivity material such as aluminum (Al), so light is reflected from both the pit and the land. The depth of the pit is made such that the phase difference between the reflected light from a pit and the land is π.

Consequently, there is destructive interference at the detector, and less light is detected. The pit depth is typically 0.13 μm.

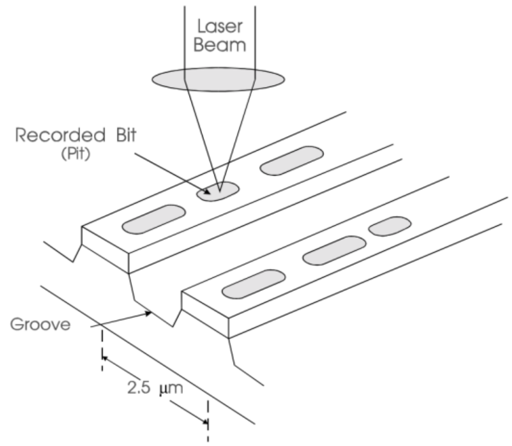

Fig. 4. Pits and land representing data bits in a CD-ROM.

2. Write-Once Read-Many (WORM) Optical Disk

A WORM (write once, read many times) disk consists of either a polycarbonate or hardened glass substrate and a recording layer made of a highly reflective substance (dye polymer or tellurium alloy). As with other optical disks, the recording layer is covered by clear plastic to protect the recording medium. WORM disk systems use a laser beam to record data sequentially. A write beam burns a hole (pit) in the recording medium to produce a change in its reflectivity. In contrast to the previously discussed read-only optical disk or CD, the WORM optical disk modulates directly the reflected intensity of the readout beam.

3. Re-Writeable, Write-Many Read-Many (WMRM) Optical Disk

An erasable and rewritable optical disk is best represented by a magneto-optic (MO) disk. The MO disk makes use of MO recording material that at room temperature is resistant to changes in magnetization. Usually, there is a separate erase cycle although this may be transparent to the user. Some modern devices have this accomplished with one over-write cycle. These devices are also called direct-read-after-write (DRAW) disks.

MULTILAYER OPTICAL DISK

While an optical disk is a 2-D optical storage device, a multilayer optical disk is in the class of 3-D optical storage. A new structure for an optical disk having up to six layers for a read-only disk and up to four layers for a WORM disk is also available.

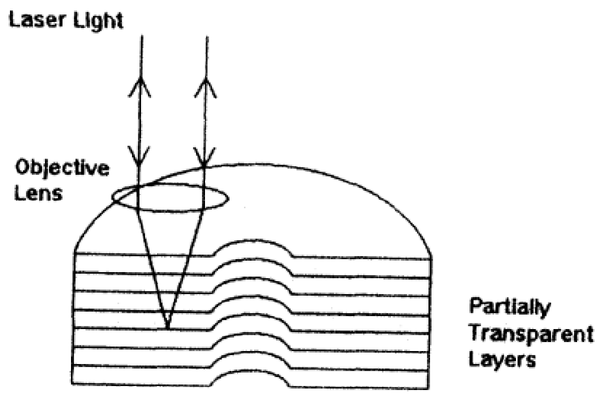

Fig. 5. Multilayer optical disk.

TYPES OF OPTICAL MEDIA

CD stands for compact disc.

DVD stands for digital versatile disc.

Blu-ray stands for Blue-ray disc which uses a blue violet laser.

	Capacity and formats	**Possible uses**
CD	650-700 MB Formats: CD-ROM, CD-R, CD-RW	CD-ROM: to include a dictionary or game CD-R: to duplicate music and data files CD-RW: to backup important files
DVD	4.7GB – 17GB Formats: DVD-ROM, DVD-R, DVD+R, DVD-RW, DVD+RW	DVD-ROM: encyclopedias, movies DVD-R: to backup information DVD-RW: to backup data files and to record audio, video
Blu-ray	25 (single-layer); 50 (dual-layer); 100 GB	To record and play high-definition TV, audio and computer data.

CALCULATING DATA CAPACITY

Blank recordable CD-R and CD-RW discs are available in two capacities: 74 minutes (both CD-R and CD-RW) and 80 minutes (CD-R only).

So, if we do the math:

74 min x (60 sec) x (75 sectors) x (2 kbytes) = 666,000 kilobytes = 650 megabytes

80 min x (60 sec) x (75 sectors) x (2 kbytes) = 720,000 kilobytes = 703 megabytes

H. W.:

Q1) In a camera, the focal length of the lens is 5 cm and the diameter of the spot is 2 cm. What is the diameter of the central spot of the Airy disk when the camera is illuminated with a collimated beam from a sodium lamp with λ = 589 nm?

Q2) (a) How many bits can be stored in an optical storage of A4 paper size (21.5 cm x 27.5 cm) using a laser diode that emits light at He-Ne wavelength of 633 nm?

(b) If the capacity of a CD-ROM is 650 Mbytes, the A4 paper size optical storage is equivalent to how many CD-ROMs?

Q3) (a) Using the same laser diode, how many bits can be stored in a 3-D optical storage having 1 cm^3 volume?

(b) To how many CD-ROMs is it equivalent?