Optical Data Storage

Philips Research

VOLUME 4

Editor-in-Chief
Dr. Frank Toolenaar
Philips Research Laboratories, Eindhoven, The Netherlands

SCOPE TO THE *'PHILIPS RESEARCH BOOK SERIES'*

As one of the largest private sector research establishments in the world, Philips Research is shaping the future with technology inventions that meet peoples' needs and desires in the digital age. While the ultimate user benefits of these inventions end up on the high-street shelves, the often pioneering scientific and technological basis usually remains less visible.

This 'Philips Research Book Series' has been set up as a way for Philips researchers to contribute to the scientific community by publishing their comprehensive results and theories in book form.

Dr. Rick Harwig

Optical Data Storage
Phase-Change Media and Recording

By

Erwin R. Meinders
Philips Optical Media & Technology, Eindhoven, The Netherlands

Andrei V. Mijiritskii
Philips Lighting, Business Unit Automotive Lighting, Eindhoven, The Netherlands

Liesbeth van Pieterson
Philips Research, Eindhoven, The Netherlands

and

Matthias Wuttig
I. Physikalisches Institut, RWTH Aachen, University, Aachen, Germany

Springer

A C.I.P. Catalogue record for this book is available from the Library of Congress.

ISBN-10 1-4020-4216-7 (HB)
ISBN-13 978-1-4020-4216-4 (HB)
ISBN-10 1-4020-4217-5 (e-book)
ISBN-13 978-1-4020-4217-1 (e-book)

Published by Springer,
P.O. Box 17, 3300 AA Dordrecht, The Netherlands.

www.springer.com

Printed on acid-free paper

Contents

1. Introduction

1.1. A brief overview of optical storage systems

Today's optical storage system stems from a small-scale product developed by Philips and commercially launched in 1978. This system was the result of the Videodisc project that was running at the Philips Research labs in Eindhoven, The Netherlands, through the 1970s. [1] It was pioneering laser-based optical storage and was based on an analogue videodisc. The product never broke the boundaries of its market niche and at its decline the number of contents titles was quite limited. However, with its optical pick-up head, servo electronics, disc mastering principles, and fine mechanics it formed a basis for the optical storage technology employed nowadays. Unlike its predecessor, the next generation system was to revolutionize the world of data storage. The fruits of a close collaboration between Philips and Sony were officially made public in 1979 in the form of a worldwide standard. The first product became commercially available in 1983 under the name of Compact Disc (CD). This was a shiny 12 cm disc carrying about 74 minutes of music in a digital format. [2] Fostered by the fast growth of computer industry a CD for computer applications – Compact Disc Read-Only Memory (CD-ROM) was introduced on the market in 1985. The disc could hold up to 650 megabyte (MB) of data and at 1x disc speed the data transfer rate was 4.3 Megabit per second (Mbps). The CD-ROM makes use of the same physical format as CD-audio but has additional error detection and correction encoding. To meet the ongoing developments in multimedia applications a number of derivatives from the original CD-ROM format have been added to the CD family. Most prominent of them were CD-interactive (CD-I) and video-CD. The CD-I format was defined to enable computer-based digital storage of data, audio, graphics and video. Video-CD is used to store 74 min of combined full-motion video and audio employing MPEG-1 video data compression techniques. Following the success of read-only discs, recordable (CD-R) and rewritable (CD-RW) media completed the family of first-generation optical disc storage in 1984 and 1995, respectively. [3] An important feature of the CD family is the high degree of interchangeability between its different family members. This was one of the main factors promoting the success of the CD optical storage system.

The tremendous technological developments of the late 80s and early 90s have created a great demand and a suitable technological basis for higher data capacities and data rates. In 1996, the second-generation optical storage system – Digital Versatile Disc (DVD) was launched. The disc accommodates 4.7 GB of data on one data layer and its DVD-video format delivers about 2.5 hours of standard-definition (SD) digital video. DVD makes use of the Universal Disc Format (UDF) to enable multimedia applications in both consumer electronics appliances and computer peripherals. It employs MPEG-2 for video compression. At 1x disc speed the system provides a data transfer rate of 11 Mbps. Besides single-layer discs, dual-layer and double-sided dual-layer configurations have been developed, with 8.5 GB and 17 GB of data capacities, respectively. Within a few years, recordable and rewritable DVD media have appeared on the market. Three mutually incompatible formats – DVD-RAM, DVD-R/RW, and DVD+R/RW, have been standardized by different industry alliances. This incompatibility has led to a so-called format war, which left both the industry players and the consumer on the loosing side. [2], [4]

In June 2002, standardization of a third-generation optical storage system was finalized. The system is called Blu-ray Disc (BD) and was proposed by the Blu-ray Disc Founders, an industrial consortium of 9 leading companies (9C consortium), comprising, among others LG, Samsung, MEI, Sony, Philips, Thomson, Hitachi, TDK, etc. [4], [5] The BD system evolved from the DVR (Digital Video Recording) project running at Philips Research labs and Sony since 1996, this time pioneering blue laser recording. [6] Many of the physical parameters proposed in the DVR system were also adapted to the BD system. The BD system features 25 GB single-layer and 50 GB dual-layer 12 cm discs and a data transfer rate of 36 Mbps. Two other data capacities are also described in the format, 23.3 GB and the reserved 27 GB. In contrast to the preceding generations, it was the rewritable disc format (BD-RE) that was described in the first version of the standard. High-definition (HD) video recording is anticipated to be the main driving force from the application side. In 2003, Sony launched the first commercial BD video recorder in Japan. Only BD-RE discs of 23.3 GB data capacity (according to version 1.0 of the BD-RE book) can be used on this recorder. In the mean time, almost all 9C companies started their own drive development activities. A major breakthrough in the proliferation of BD is the successful introduction of the triple-writer optical pick-up unit (OPU) by Philips, ensuring backwards compatibility up to the first generation optical discs. This OPU can actually read and **write** CD, DVD and BD type of discs. Next to Blu-ray Disc, another third-generation system has been proposed. This system is currently being standardized under the name of HD-DVD (high-definition DVD) and has some major physical differences from BD. A main difference with the BD system is the lower data capacity of 15 GB; a dual-layer version makes 30 GB storage capacity. The future of both systems is unclear as yet. One of the serious issues the optical storage industry has to deal with is copy protection (CP) and digital rights management (DRM) of the data stored on the discs. There is a high probability that success of the upcoming generations of optical storage systems will be determined not only by their storage and retrieval performance but to a large extent by the availability and versatility of CP/DRM solutions.

So, by the time this book is being written two generations of optical storage systems and a plurality of often competing formats have been successfully commercialized. The 'war' on the third generation 'blue' systems has just started. It seems that the first recordable high-density systems will be utilizing the BD format with a disc capacity of up to 50 GB. Foreseen applications are a high-density video recorder and a PC drive. The high-density format allows also for a smaller-form factor drive, such as a Camcorder. The availability of BD-ROM media is of strategic importance for the proliferation of the BD format. But the willingness of leading film studios and content distributors to publish high-definition content in BD-ROM format depends very much on their confidence in the copy protection system of BD-ROM.

While the market introduction of the third generation optical recording system just started, options for a fourth generation system are already under development in the research labs of several companies. In accordance to the evolutionary increase in data capacity, the near-field system utilizes an increased numerical aperture objective lens to allow for a 100GB single layer data capacity. [7] Also advanced signal processing widens the system margins and enables a single-layer storage capacity of up to 50 GB. [8] Two-dimensional optical storage is a possibility to increase data transfer rates but this system requires a multi-pot readout system. [9] Data capacities of Terabytes are envisioned if the third dimension is explored, so-called volumetric data storage. Recent improvements in recording materials have renewed interest in holographic data storage. [10] Besides the tremendous data capacity, page-based storage involves also a relative high data-transfer rate. Other examples of volumetric data storage are electrochromic media, in which the individual data layers are independently addressable. [11] The University of Arizona explores currently an evolutionary optical storage system based on DNA carriers. [12] Although this system is far away from commercialization, it is based on a very interesting and novel concept.

Nowadays an attractive property portfolio, which includes removeability, robustness, interchangeability, low price, characterizes optical storage media and 'cool' look. But what is the physical difference between the different storage generations and how does it work all together? In what follows the principles of optical data storage will be explained on a basic level.

1.2. The basics of optical storage

1.2.1. Optical drive layout

An optical storage system consists of an optical drive and corresponding optical media. The main elements of an optical drive are a semiconductor laser, a set of optical elements to shape and focus the laser beam, a disc driving part, and a signal detection system. In Figure 1, a simplified layout of an optical drive is shown. A light beam generated by the laser propagates through the optical elements of the drive and is focused into a diffraction-limited spot on the disc. Being reflected by the disc, which carries user and service information, the beam is projected onto a set of photo-detectors. The detected signals are subsequently processed by electronics of the drive (not shown in the figure). Among the most important parameters that characterize an optical storage drive are the wavelength (λ) of the laser and the numerical aperture of the objective lens. The numerical aperture is defined as NA = $\sin\alpha$, where α is the angle between the optical axis and the marginal ray of the converging beam in air. As will be shown below, these parameters determine the storage density of the system.

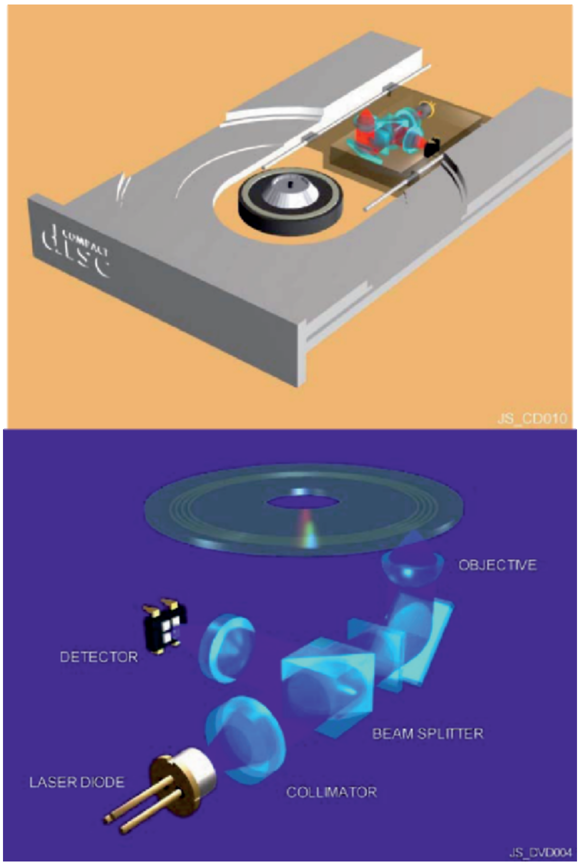

Figure 1. Schematic drawings of an optical storage system. The upper image represents an optical drive to house the disc. The lower image shows a schematic of the optical path with laser, optics, detector and objective lens.

1.2.2. Basic principles of optical data storage

The principle of optical data storage and retrieval is explained in Figure 2 in a simplified form. The audio and video signals perceived by users are of analogue nature. It is, however, more convenient and robust to use the digital domain to efficiently store, transmit, and retrieve such signals. For this purpose analogue-to-digital conversion (A/D conversion) is done and additional data bits facilitating error correction (error correction coding, ECC) are added. In its digital form the user data is a binary code represented by a sequence of bits defined as logical “1”s and “0”s.

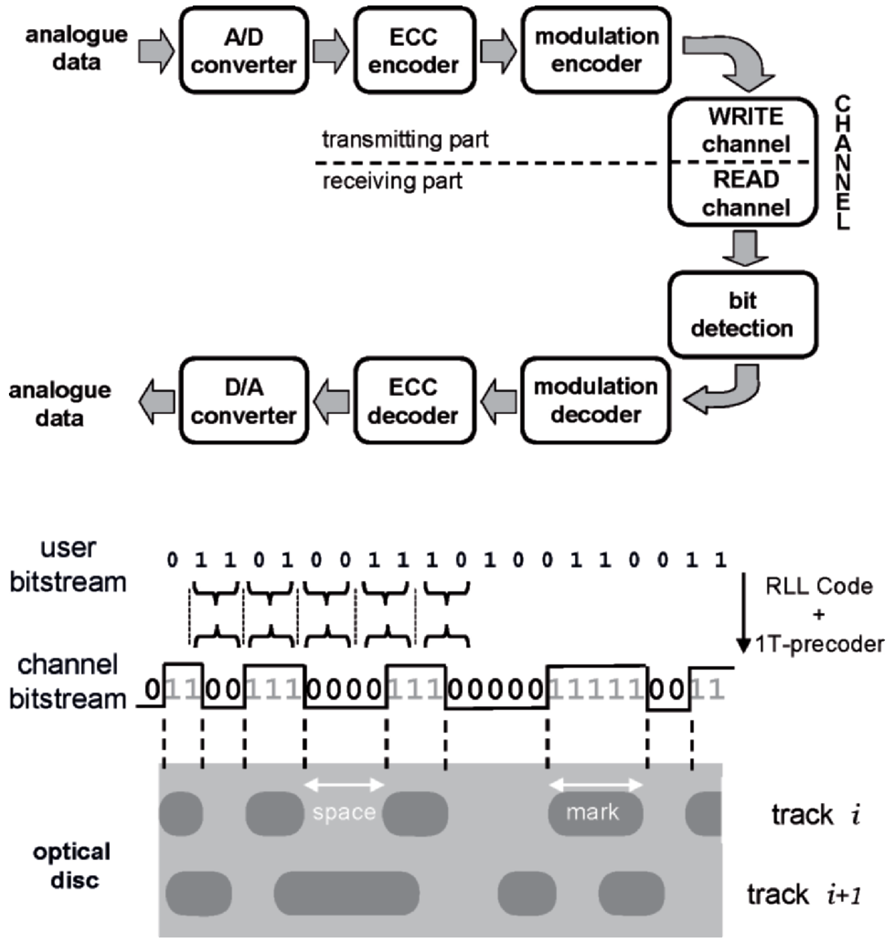

Figure 2. Principles of optical data storage. The upper panel represents a schematic flow chart of the information flow in an optical storage device. The lower panel denotes a typical data pattern in an optical disc and the corresponding channel and user bit stream.

In optical discs, data is represented by small areas (marks or pits) with optical properties that are different from the optical properties of the surrounding matrix. Marks (pits) and spaces (lands) between them are often referred to as (marking) effects. Typically, an optical medium is designed such that the reflectivity of marks (pits) is lower than the reflectivity of the surrounding matrix at the laser wavelength used. In case of recordable and rewritable media, the written areas (marks) have an intrinsically different reflectivity upon thermal degradation. Amplitude modulation is the main mechanism for readout of data. ROM media are mass-replicated and are in most cases provided with a metallic mirror. Constructive and destructive interference of the focused laser spot causes modulation, also referred to as phase modulation. To adapt the binary data pattern to the modulation transfer characteristics of the optical channel, modulation coding is applied. In this process the user data is encoded in the length of the effects (the so-called run-length limited, RLL, coding), which is an integer times a unit-length, the so-called bit-length. To obtain an optimal match to the spatial frequency characteristics of the optical channel and to achieve optimum data density a set of lengths is employed. In the case of CD and DVD a set of run lengths with a minimum of 3 and maximum of 11 channel bits is used. In the case of BD, the 2-to-8 set is used. More details on encoding and error correction can be found elsewhere. [13] The marking effects are placed in data tracks, which typically form a concentric spiral on the disc substrate. To retrieve the information detection of the marking effects, decoding and subsequent conversion into analogue signals are done. The optical parameter that is utilized to detect the effects is the intensity of the laser light reflected by the disc. Upon readout the disc spins and the focused laser beam scans the data tracks passing over the effects. The reflectivity level difference between marks and spaces (the optical contrast of the effects) and the interference in the laser light diffracted by the effects pattern yield intensity modulation of the reflected laser beam. In order to establish the lengths of the effects the intensity profile is sliced through and sampled with a predefined frequency, which is derived from (and, therefore, synchronized with) the rotational frequency of the disc.

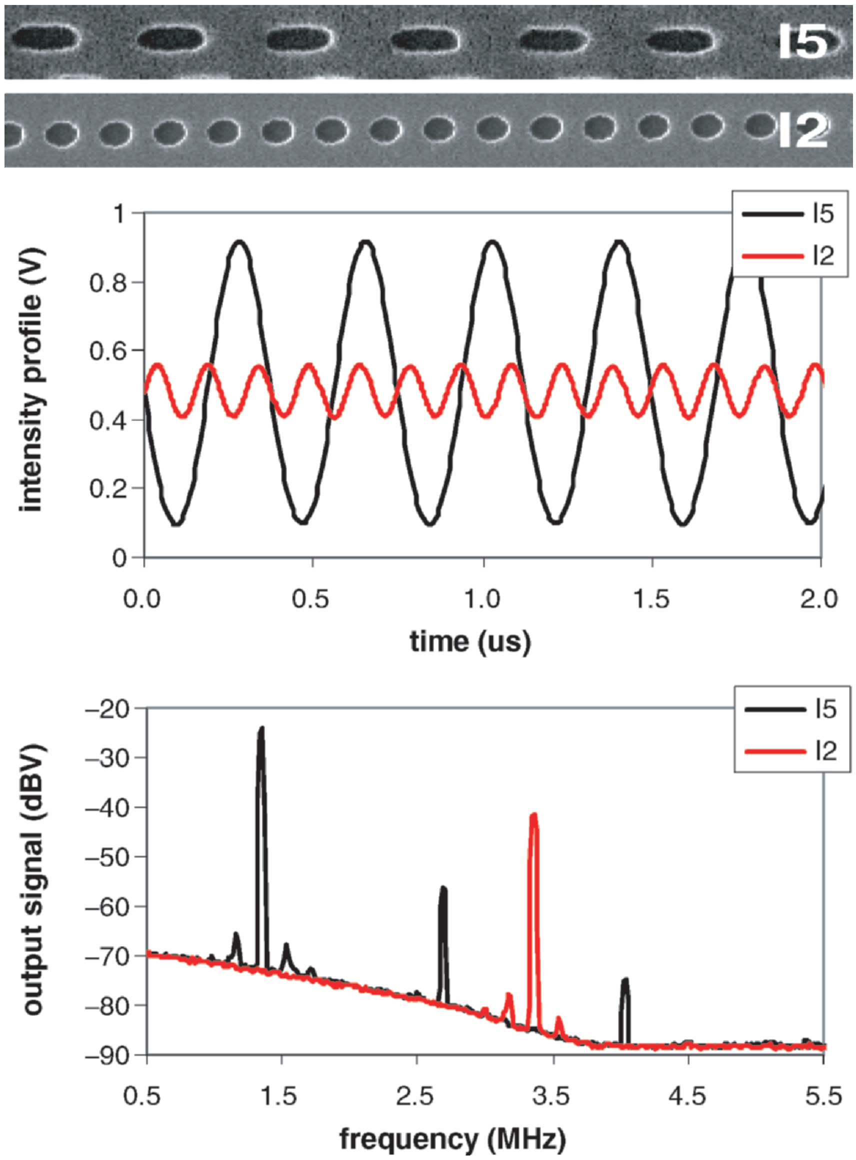

Figure 3. Time (upper plot) and frequency (lower plot) domain signals from single-tone data carriers (I2 refers to a 2T single tone; I5 refers to a 5T single tone).

To give a simple example, modulation profiles of two different single-tone data patterns are plotted in time and frequency domains in Figure 3. An important fact that can be derived from the plots is that in the case of the single-tone carrier with shorter effects (higher frequency) the modulation amplitude is smaller compared to that of the single-tone carrier with longer effects (lower frequency). There are two reasons to explain this. One is the relative area of the effects with respect to the effective laser spot size on the disc. The other is the frequency dependence of the modulation transfer function (MTF), which describes the optical response of a spatially modulated pattern of effects on the disc. In central-aperture-detection systems, MTF decreases monotonously down to zero at a spatial cut-off frequency $cf=2NA/\lambda$, where NA and λ are the numerical aperture and the laser wavelength of the system (see Fig. 4). The cut-off frequency limits the maximum information density that can be stored on the disc.

In the frequency domain such single-tone patterns (single-tone data carriers) manifest themselves as peaks at the frequencies (main frequency plus higher-order harmonics) corresponding to the spatial-frequencies of the effects on the disc. Translated into the signal domain, the signal frequencies that can be extracted from an optical disc are smaller than $2\nu NA/\lambda$, where ν is the linear velocity of the spinning disc.

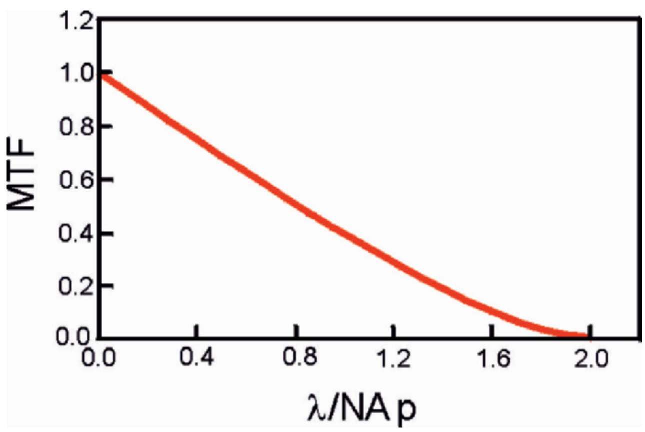

Figure 4. Modulation transfer function of a central-aperture optical channel.

As may be obvious from the above, bit detection is directly related to accurate measurement of the intervals between the slicer crossings in the time domain. Any deviation in lengths of the effects, irregularities in their shape or in local disc reflectivity, cross talk with the neighboring tracks, as well as fluctuations in electronics and laser performance etc. will inevitably alter the intensity modulation profile and affect detection. In panels (a) and (b) of Figure 5, two intensity modulation profiles obtained for a random sequence of bits are shown. These intensity modulation plots are called the eye-patterns. The eye-pattern in panel (a) corresponds to a perfect case. The eye-pattern in panel (b) corresponds to a case where imperfections are present. As can be seen from the figure the presence of imperfections causes spread in the intensity modulation profiles. When the sources of fluctuations are Gaussian in character, the standard deviation of the Gaussian time distribution is called *jitter* and is expressed as percentage of the clock-time: $jitter=\Delta t/2T\times 100\%$, where Δt is the spread at the slicer-level crossings and T is the time-period. Each mark and space (pit and land) length can be defined as its average length in time domain and jitter in percent of clock-time. An increase in jitter manifests itself in the time-frequency domain as a decrease in the signal strengths, which is characterized by the signal-to-noise ratio (SNR). The relation between jitter and SNR can be expressed as $jitter=½\times 10^{-SNR/20}\times 100\%$.

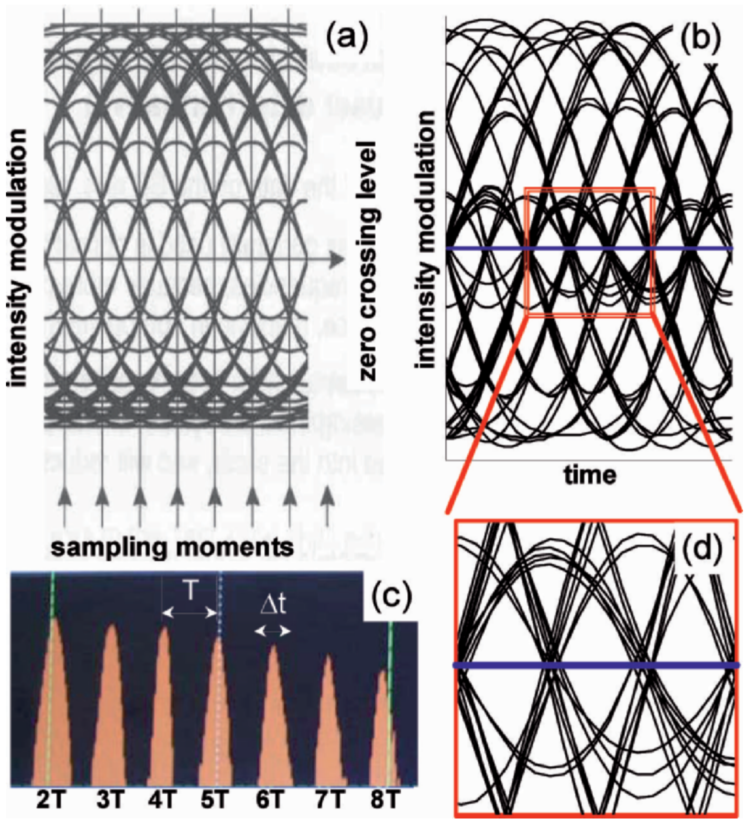

Figure 5. a – eye-pattern calculated for a perfect case; b – eye-pattern with imperfections included; c – measured jitter histogram for a 2T. 8T data pattern; d – magnified section of panel (b).

When analyzing recording media the concept of carrier-to-noise ratio (CNR) has proven to be useful. This CNR is the SNR of a single-tone data carrier written on the disc. By contrast to normal SNR, CNR is measured in a narrow bandwidth centered at the carrier frequency.

In turn, full bandwidth SNR is related to the bit error rate (BER), which is ultimately a figure of merit for the quality of data storage and retrieval. The relationship between BER and SNR for a threshold detection system is given in Figure 6, which displays a pronounced increase in BER with decreasing SNR. The science behind this graph can be found elsewhere. [14]

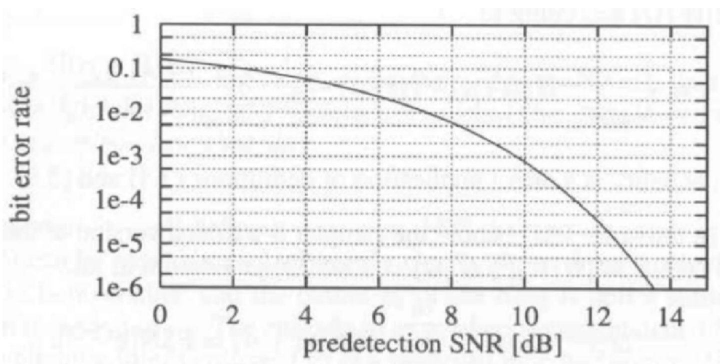

Figure 6. Dependence of bit error rate on signal to noise ratio over total bandwidth, taken from [14].

To facilitate bit detection, *equalization* is typically employed in optical storage systems. [15] An improvement is achieved by electronically boosting the high-frequency response and, in this way, increasing the amplitude of intensity modulation generated by the smaller effects. On the media side, enhancing the optical contrast of the marking effects can increase the modulation amplitude. This aspect will be discussed in the upcoming chapters.

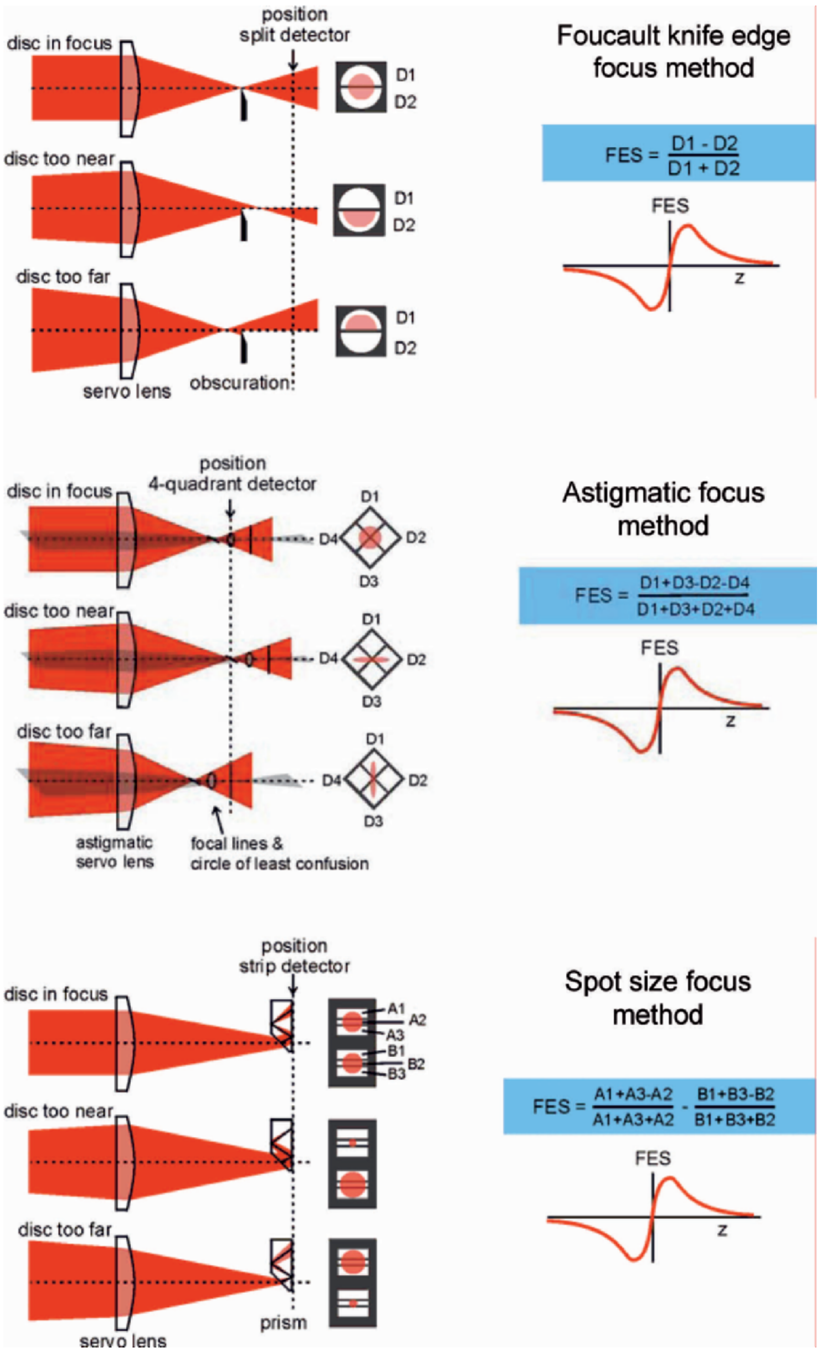

Figure 7. Focusing methods.