Future Generations Optical Storage Systems

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1. Introduction

During the past two decades CD and DVD optical recording systems provided us with an overwhelming data storage capacity. Furthermore, the storage density of both CD and DVD largely exceeded the density obtained by other recording technologies. In recent years, however, the situation has changed due to the increased pressure from competing technologies. Especially the 60 to 100% annual density increase realized in magnetic hard disc recording calls for new distribution media with comparable capacities. Digitalization of entertainment industry requires high-capacity, removable and cheap storage media for distribution of their digital content. In this respect, the removability of the storage media in optical recording is clearly a major advantage.

Storage capacity in optical disc recording is directly related to the size of the laser spot focused on the information layer, being determined by two fundamental quantities – the wavelength of the laser light, and the numerical aperture (*NA*) of the objective lens. Pushing systems towards higher densities by increasing, the *NA* and by using lasers with shorter wavelengths inevitably leads to tighter system tolerances. Robust readout under these circumstances can either be achieved at the expense of increased drive complexity or by putting more stringent requirements on the disc media.

New optical recording systems will emerge on the market, being a result of the evolution of classical compact disc technology, still having numerical apertures less than 1. A more revolutionary and exciting development of recent years is the dawning merge of optical and hard disc technologies, yielding optical readout with an effective numerical aperture of greater than 1. A range of new products can be developed after combining the best elements of these two techniques, thereby boosting the storage capacity and reducing the cost per bit.

2. CD and DVD

Optical media of the CD-generation are transparent 1.2 mm thick discs with a pit or groove structure at the disc side opposite to the one facing the optical pickup unit (OPU). The laser beam is focused through a relatively thick substrate on the information layer thus ensuring effective protection against dust or fingerprints. Along with CD-ROM there appeared a family of recordable and rewritable systems. At present the CD-R and CD-RW standards have become very popular. A clue to their success lies mainly in their compatibility with the installed base of CD-ROM and CD-audio drives. Both CD-R and CD-RW exploit reflection changes of a recording layer under thermal influence of a focused spot of a high-power laser. Those reflection changes can be either permanent (CD-R, data is burned into a polymer dye layer) or reversible (CD-RW, thermally induced crystalline/amorphous phase transition in a phase change layer). Upon read out, the differences in reflection between a "0" and a "1" cause light intensity modulation which is, although smaller in magnitude, similar to that produced by replicated pits of a CD read-only disc.

When the CD standard was defined in the early eighties, infrared laser diodes (GaAs, 780 nm) were commercially available. Due to their compact size and potentially low cost these laser diodes made the CD the success it has become now. A straightforward way to increase the storage capacity in optical recording is reducing the wavelength of the optical pickup laser beam and/or increasing the numerical aperture of the objective lens. In the early nineties red laser diodes became available and the DVD standard was born. The introduction of DVD marked a seven-fold increase in recording density as compared to CD, achieving 0.74 Gbyte/in² (9.2 million bits per squared mm). About half of this gain (a factor 2.6) was realized by using an objective with a higher numerical aperture, $NA=0.6$, and a laser with a shorter wavelength, $\lambda=650$ nm (for CD those parameters were $NA=0.45$ and $\lambda=780$ nm). An additional reduction in format parameters like track pitch and bit length gave DVD its capacity of 4.7 Gbytes, enough for 2.5 hours of playing time of standard definition video. It required the development of several novel technologies. To achieve sufficient optical tolerances (for details see below) the substrate through which the focused laser beam reaches the data layer became thinner, i.e. 0.6 mm in stead of 1.2 mm for CD. For mechanical stiffness two substrates with thickness 0.6 mm are glued back-to-back, which required a new technology for such compound disc fabrication.

The replicated Digital Versatile Disc is meant to become the second generation distribution medium and was primarily developed to carry video and multimedia software. Following the success of the CD family several recordable and rewritable DVD standards have been put forward by different companies. They include DVD-R (recordable, 4.7 Gbytes), DVD-RAM (rewritable, 2.6 Gbytes), DVD+RW and DVD-RW (rewritable, 4.7 Gbytes) systems. The success of the CD-family has taught us that compatibility has strong appeal to the consumer, therefore the system of choice most probably will have the same capacity as single-layer DVD-ROM (read only, 4.7 Gbytes) and will be fully compatible with DVD-ROM and DVD-video players. The DVD-video format is becoming a success nowadays given the fact that the number of DVD-video players sold worldwide is increasing rapidly. Although a "format war" is going on for the DVD-rewritable systems (comparable to the war between the Betamax, Video2000 and VHS magnetic tape systems in the late seventies), the first video recorders based on the DVD standard are emerging on the market today.

3. Aberrations and System Aspects

In order to obtain a diffraction limited spot at the data layer of an optical disc the total light path from laser to disc has to be free of optical aberrations. For instance tilt and thickness variations of the optical components in the light path (including the disc itself) may lead to coma, astigmatism and/or spherical aberrations, thereby blurring the readout spot. A convenient quantity to express the magnitude of these aberrations is the phase deviation (RMS value) of the laser beam wave front from a plane wave, denoted as $\boldsymbol{W}$. It can be shown [3] that this total deviation $\boldsymbol{W}$ is a quadratic sum of all possible aberrations in the optical system: $W^2 = W^2_{spherical} + W^2_{astigmatism} + W^2_{coma} + \Sigma\, W^2_{higher\ order\ terms}$. The criterion for a diffraction limited spot at the focus of the objective lens is then $\boldsymbol{W} < 0.07\,\lambda$.

Variations in the thickness of the substrate through which the laser beam is focused before it reaches the data layer, lead to spherical aberration of the spot, its value being proportional to the fourth power of the NA:

$$W_{Spherical} \propto \frac{\Delta d \cdot (NA)^4}{\lambda} \qquad (1)$$

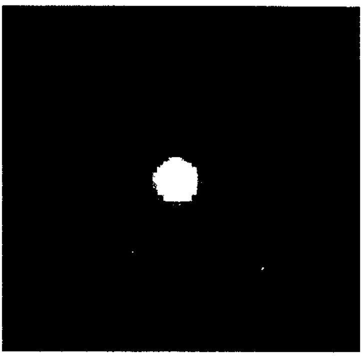
where Δd is the deviation from the nominal substrate thickness. Furthermore, disc tilt with respect to the optical axis causes comatic aberration:

$$W_{Coma} \propto \frac{\theta \cdot d \cdot (NA)^3}{\lambda} \qquad (2)$$

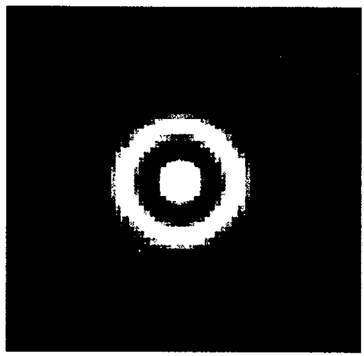
where θ is the tilt angle (i.e. the angle between the objective lens and the disc surface), and d is the substrate optical thickness. As we will see in the next section the storage capacity of an optical recording system can be increased considerably by increasing the numerical aperture of the objective lens. However, optical aberrations scale with higher powers of the NA, and consequently readout of a DVD-like substrate with a high NA (>0.6) objective becomes more and more difficult.

As an example figure 1 illustrates the degradation of the readout spot after focusing by a $NA = 0.85$ objective lens through a DVD-like 0.6-mm substrate. A more rigorous treatment of disc aberrations is presented by Braat [1].

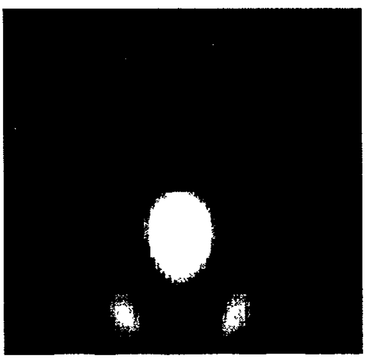
A plain spherical lens introduces spherical aberration, giving rise to a blurred spot at the data layer of an optical disc with dimensions greater than the diffraction limit (i.e. spot diameter $\approx \lambda/NA$). In order to obtain a



(a) diffraction limited spot



(b) blurred spot due to spherical aberration



(c) blurred spot due to comatic aberration

Figure 1:
Readout spot aberrations as a function of disc tolerances (a) aberration-free spot of 650 nm laser focused by an objective with $NA = 0.85$ through a substrate with 0.6mm tickness (b) and (c): the same spot aberrated due to disc imperfections; (b) disc thickness error of 30 µm, (c) disc tilt of 0.5°. Both mechanical deviations are within the DVD disc specifications but lead to unacceptable deterioration of the high-NA readout spot.

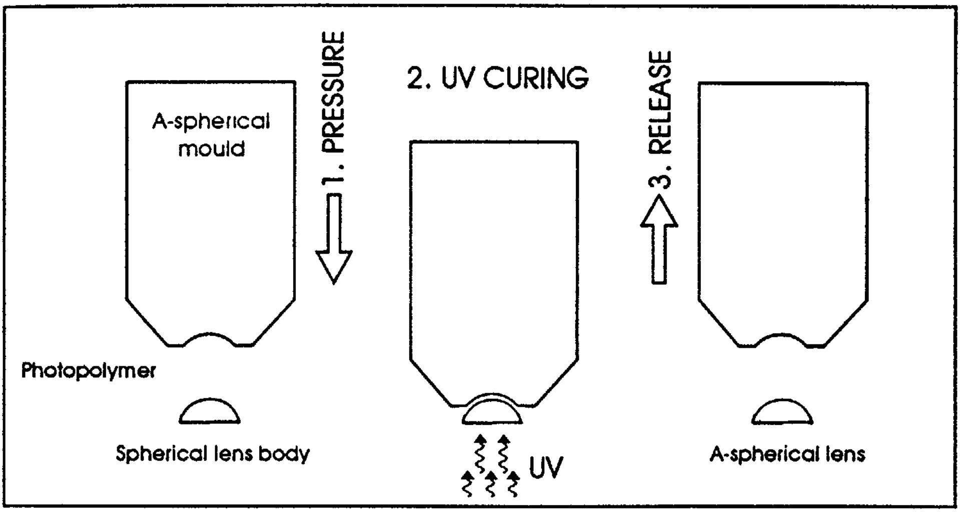


Figure 2:
Glass-photopolymer aspherical lens replication technique. A liquid photopolymer lacquer is compressed by an aspherical mould (made by diamond turning) on top of a spherical lens body. Next the lacquer is cured by UV radiation and the aspherical lens is removed from the mould.

diffraction limited focused spot, the objective lens consist of one or more aspherical surfaces. Since spherical and comatic aberrations scale with higher powers of the *NA*, the tolerances in making such aspherical surfaces become more severe for high *NA* objective lenses. A very elegant technique to obtain an aspherical lens surface is to start with a spherical glass body and to apply a plastic layer with the correct form factor on top of the glass sphere by a replication technique (see figure 2). The geometric form factor of this aspherical layer can be chosen such that it compensates for a certain amount of spherical and comatic aberrations to be expected in the optical disc system (due to for instance variations in disc thickness or disc tilt with respect to the objective lens).

A single-element objective lens with a *NA* significantly higher than 0.6 poses a major challenge in terms of manufacturing and alignment tolerances (use of *field*), and becomes simply impractical for an objective with $NA > 0.7$. An obvious step to circumvent the problem is to shift to a two-element lens design [2]. With the optical power divided over two lens elements, *i.e.* four refracting surfaces instead of two (for single-element objective lens) and a suitable choice of the glass materials and aspherical surfaces, a 2-element objective lens of the *NA* as high as 0.85 becomes manufacturable.

One way to control the optical aberrations when reading a DVD-like disc ($d = 0.6$ mm) with a $NA = 0.85$ objective lens is to use a special mechanical actuator with several additional degrees of freedom that would actively compensate the errors of a rotating disc by adjusting the angle between the two lens bodies of the $NA = 0.85$ objective. This actuator adjusts dynamically the position of one of the two lenses of the dual-lens objective in response to the disc tilt. A more detailed description of the system employing this actuator can be found elsewhere [3]. The above approach has the great advantage of full readout compatibility with the existing DVD-format and being a straightforward extension of disc manufacturing technology. The drawback, on the other hand, is the need to resort to a complex actuator controlling the angle between the two elements of the objective lens.

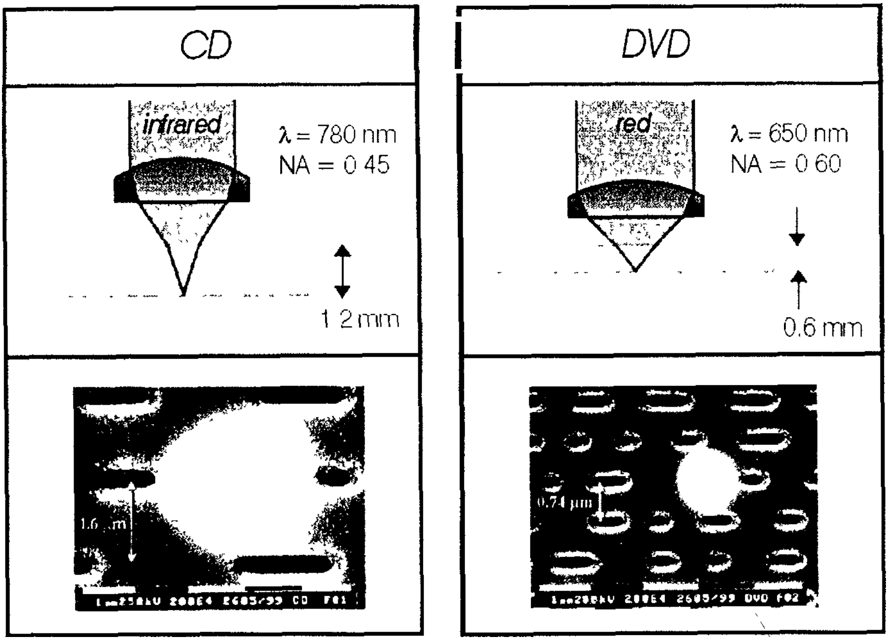
Another elegant solution is obtained by reducing *d* in formulae (1) and (2) and accessing the data through a relatively thin (100 μm) optically transparent cover [4]. According to formula **Fout! Verwijzingsbron niet gevonden** this would relax the requirements on disc tilt. The challenge of obtaining sufficiently low readout spot aberrations is hereby transferred to the manufacturing of a 100 μm thin cover layer. This approach is the basis for a new optical recording standard: DVR.

4. Third Generation Optical Recording: DVR

Although DVD is still a relatively young product (introduction in 1997) and the battle between the different DVD-rewritable formats still has to be fought, rapid developments of several technologies in a very short period of time bring a third step in storage density at close hand. In 1999 a Japanese company, Nichia Corporation, announced a major breakthrough in the R&D quest for the holy grail of optical recording: the blue laser diode. In december last year their blue laser diode (GaN, 390-420 nm) became commercially available, having lifetimes of several 1000 hrs at operating powers of 5 mW cw at room temperature. Recently Philips and SONY defined an optical recording standard based on a blue laser (405 nm) and a high numerical aperture ($NA = 0.85$) objective lens [5]. This standard, DVR, being an acronym for Digital Video Recording, enables a storage capacity of 22.5 Gbytes on a single-layered rewritable optical disc with CD-like dimensions (12 cm diameter). Apart from its huge storage capacity, the data rate for writing data to a DVR disc has been increased considerably compared to the DVD standard, paving the way for home video recording of high definition video (HDTV) broadcasting. First HDTV broadcasting has started recently in the US and Japan, and will be introduced in Europe soon, triggering the need for video recorders based on this third generation optical recording standard.

After combining a blue GaN laser ($\lambda = 405$ nm) and an objective with $NA = 0.85$ the storage density for DVR can be increased up to 3.6 Gbytes/in^2 (45 million bits/mm^2). The price to pay for achieving this gain in storage capacity in going from DVD to DVR (by reducing the wavelength and increasing the *NA*) is a more complicated optical pickup unit with tighter system tolerances. The very elegant concept used in CD and DVD of having a thick substrate through which the data can be addressed (and hence being relatively insensitive to dust and/or scratches on the disc surface) cannot be used in combination with a high *NA* (>0.7) objective. In this case disc tilt would result on comatic aberration. This led to the thin cover layer approach used in the DVR standard, where a 100 micrometer thick film is protecting the underlying data layer. The cover is supported by a thick substrate, which provides the mechanical stiffness. *Such a disc consists of a* 1.1-mm thick polycarbonate substrate, which can be fabricated by cheap injection molding.

To further increase the tolerance margins for the lens manufacturing and assembling, the free working distance of the DVR objective has been reduced to 150 micron. This on its turn leads to an increased risk of having a lens – disc crash, possibly damaging the disc surface or the objective lens. Hence faster servo mechanics and electronics is needed to control and fix the distance between the objective lens and the disc. In figure 3 an overview is given of the three generations optical recording standards: CD, DVD and DVR.



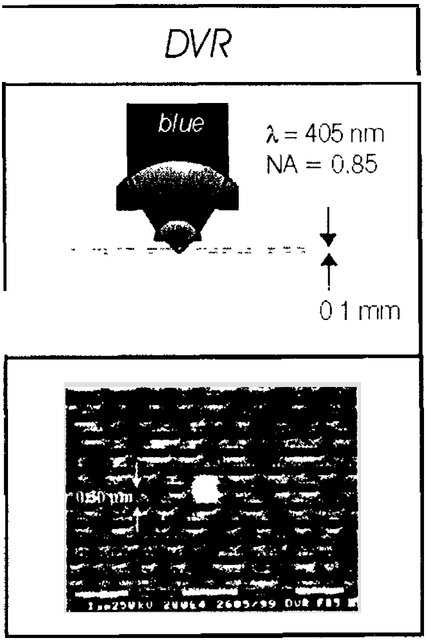


Figure 3:
A comparison of the 3 generations of optical recording. CD, DVD and DVR.

Although it may seem that building a working DVR system may be a rather difficult task, recent technological advances (coming forth from a perfect marriage between optics, mechanics and electronics) allow a proper balancing of tolerances between the different system components. The first DVR drives are operational in our research lab and show overall system tolerances even better than for DVD. The price to pay is the use of a cartridge to protect the disc from dust and fingerprints, and a strong error correction coding to recover from potentially erroneous readout of data.

5. Fourth Generation Optical Recording: Near Field Recording

The numerical aperture of an objective lens operating in air is fundamentally limited to unity:

$$NA_{Air} = n_{Air} \cdot sin(\theta_{Marginal}) = sin(\theta_{Marginal}) \leq 1 \quad (3)$$

where n_{Air} = 1 is the index of refraction of air, and $\theta_{Marginal}$ is the angle that the marginal rays form with the optical axis at

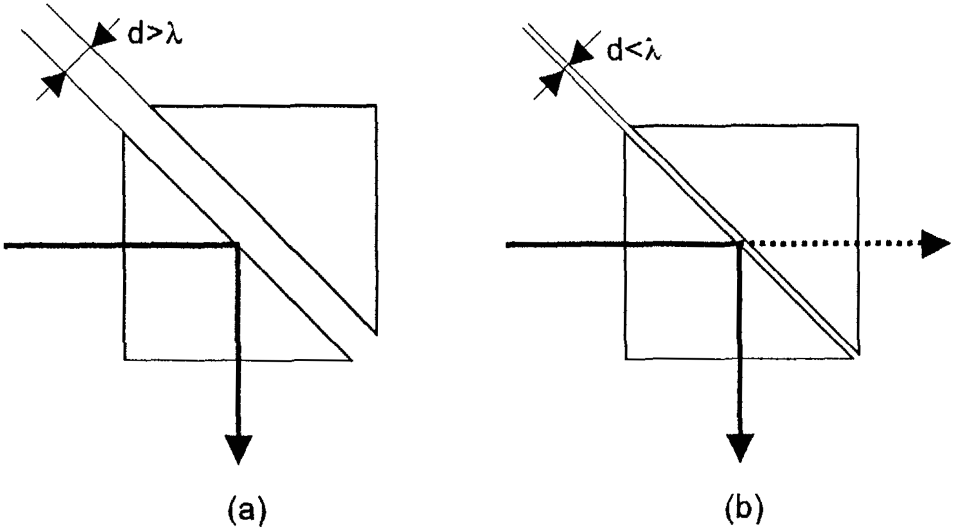


Figure 4:
Total internal reflection (TIR) of light at the glass-air surface can be frustrated by bringing another piece of glass in close proximity to this surface (d<λ). (a) total internal reflection; (b) frustrated total internal reflection

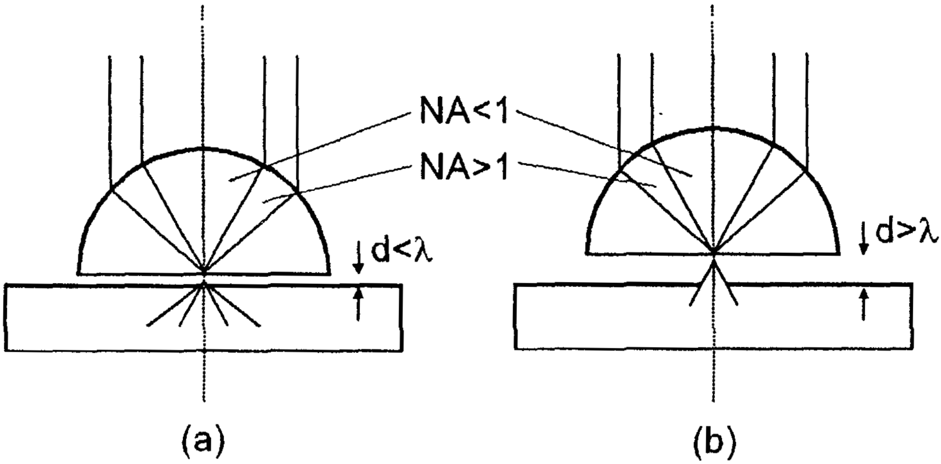


Figure 5:
Solid immersion lens technology for near-field recording. A numerical aperture greater than unity can be achieved via evanescent wave coupling to the disc substrate (a). For CD, DVD and DVR the distance between lens and disc d>>λ, and evanescent wave coupling does not occur (b).

the focal point. The maximum value of the *NA*, however, increases when the beam is focused in a highly refractive medium, as the limiting value is then equal to the value of the refraction index of the medium. This principle is widely used in so-called immersion microscopy where the object under investigation is submerged in a highly refractive liquid, typically oil. For data storage application it has been proposed to form a spot within a highly refractive lens element (solid immersion lens), positioned in close proximity of the recording layer [6,7]. If the distance between the lens and the disc is large the rays corresponding to $NA > 1$ will experience total internal reflection (TIR) at the last lens surface and consequently they will never reach the disc. It is well known however that TIR can be frustrated by bringing another piece of material with high refractive index in close proximity to the lens surface whereupon TIR takes place (see figures 4 and 5). In fact, the optical disc itself can play the role of this second material. Since the numerical aperture is above unity, so-called evanescent waves take part in the spot formation. As these evanescent waves decay exponentially at distances comparable to the wavelength of light, the air gap between the objective lens and the disc must be of the order of $\lambda/10$ and less, corresponding to 40 nm for a blue laser. Such lens-disc separation is comparable to the distance between a magnetic head and the disc in current generation hard discs. To realize such spacing an air-bearing slider "flying" above the smooth disc surface is commonly employed. For optical recording such a slider will be made of transparent material with high refraction index and will carry a solid immersion lens instead of the magnetic read/write head. For such a small spacing contamination control will present a great challenge. Indeed, the optical disc being a removable medium will come in contact with dust particles that are comparable with the disc-lens spacing and can jeopardize both the medium and the readout head. Therefore future optical discs will probably be enclosed in protective cartridges.

6. Conclusions

In the coming years optical recording will speed up its pace of innovation. In order to increase the information density, objective lenses with very high numerical apertures, and lasers with short wavelength (blue-violet part of the electromagnetic spectrum) will be used. Simultaneously, the transparent layer thickness will reduce from 1.2 mm (CD) via 100 μm (DVR) to virtually zero (near-field recording). Future recording technologies are expected to shift from purely optical or purely magnetic to some kind of combination of both, featuring storage capacities up to 100 Gbytes on a single-layered disc.

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