Chapter 7

Applications of the models to optical storage systems

In the following chapter applications in the field of optical storage systems for the computational models of the scanning microscopes described in chapters 5 and 6 are described in detail. In particular the signal generation process in the CD-ROM, phase change and magneto-optic storage systems is presented.

Finally the transfer function approach is utilised for investigating channel optimisation techniques for modifying the transmission properties, and hence the spatial frequency characteristics, of the optical channel. This is a form of optical equalisation, analogous to the usual electronic equalisation used in the data recovery process in storage channels

7.1 Introduction to optical storage formats

The advancement in computer technology and the introduction of the information superhighway has led to the need for high data storage capabilities. In its early beginnings computer data was read from punched tape or computer cards which would be fed into the computer and read mechanically. However, as the use and the size of computers grew the use of such storage technologies became inefficient and slow. Hence, the need for higher data storage capabilities and more efficient data rates led to research into more powerful and precise means of data storage; magnetic storage media was introduced. Originally in the form of magnetic tape, magnetic media soon developed into two forms: floppy and hard disc storage. The hard disc has now firmly established itself as the de facto standard for data storage in computer systems.

Optical storage technology was introduced as an alternative storage medium to magnetic hard discs. Using a diffraction limited laser spot to write and retrieve data promised high data storage capabilities whilst maintaining small size storage media. The advantages of optical storage soon became clear, optical systems offered Gbyte / disk storage abilities and non contact head to medium read / write capabilities, so avoiding head crash problems associated with magnetic hard disc storage and providing disc inter-changeability.

The early optical storage technology, the **CD** (**C**ompact **D**isc) and later the **CD-ROM** (**C**ompact **D**isc **R**ead **O**nly **M**emory), were read only. Here data is pressed into the disc during the manufacturing process and cannot be altered thereafter. Data readout is accomplished by detecting the change in phase introduced into the readout beam as the disc is scanned beneath the focused spot. Write once systems, or **WORM** (**W**rite **O**nce **R**ead **M**any) systems use high power laser beams to alter the surface of a recording layer. The writing of data can be performed using a variety of techniques including *ablative recording* where the data is physically burnt into the surface of the recording layer, *dye/polymer recording* where marks are formed in organic films by the wavelength selective absorption of light or *phase change media* where the reflectance properties of the information layer are changed by a high power laser beam. Information retrieval is performed by detecting the change in reflectance of the disc as it is scanned beneath the focused spot. The problem associated with WORM systems is that the data can only be written once, ideal for data archiving, but not very useful for common data storage applications. The introduction of phase change media for read / write purposes and the introduction of magneto-optic storage systems led to the realisation of optical storage systems offering high data storage capacity with the added advantage of being able to read, write and erase data [18,19,77,78].

The readout channels of the CD-ROM and phase change systems are analogous to that of the Type 1 reflectance scanning microscope and the readout channel of the MO systems is analogous to that of the Type 1 differential detector scanning microscope described in this thesis. As a result, the theoretical and computational models of this thesis can be used to predict the readout performance of most forms of optical data storage.

7.2 The CD-ROM optical system

The compact disc, or CD as it is commonly known, was developed by Philips and Sony in the late 1970s and early 1980s. Initially CDs were produced as an alternative storage media to vinyl LPs and cassettes in the music industry, due to their light weight, small size (120mm diameter), high durability, low manufacturing costs and high data storage capabilities. The success of the CD was a revelation leading to it establishing itself as the de facto standard for audio storage and reproduction by the late 1980s. In the 1990s the compact disc read only memory, CD-ROM, was introduced for the distribution of software, catalogues and large data-bases for computer end users. The CD-ROM has become the standard storage media for commercial software, due to the large amount of digital data, 600Mbytes , that can be stored on a single disc, compared to other interchangeable storage media, such as the 3½ inch magnetic floppy disc that can hold a meagre 1.44Mbytes of data. The low cost of CD-ROM drive units has led to the CD-ROM establishing itself as a common storage peripheral alongside magnetic storage devices in computer systems.

A CD is a polycarbonate disc that has an outer diameter of 120mm, an inner circular cut-out of 15mm and a thickness of 1.2mm. The disc comprises a transparent substrate, an information layer and a reflective coating. The substrate is produced using an injection moulding process, and the spiral track of data is recorded into the substrate using a stamping, or pressing, process. The aluminium reflective layer is then coated over the information layer. The purpose of the aluminium coating is to make the surface behind the information layer reflective, to aid in signal detection.

The data held in the spiral track is represented by a series of holes, or pits, in the surface of the substrate. The length of these pits is governed by the coding scheme and the stored digital data. Figure 7.1 represents a small portion of the information layer on the CD-ROM disc. The length of the pits is restricted by the coding scheme to vary from 0.83μm to 3.56μm, at a track width of 0.5μm and track spacing 1.6μm.

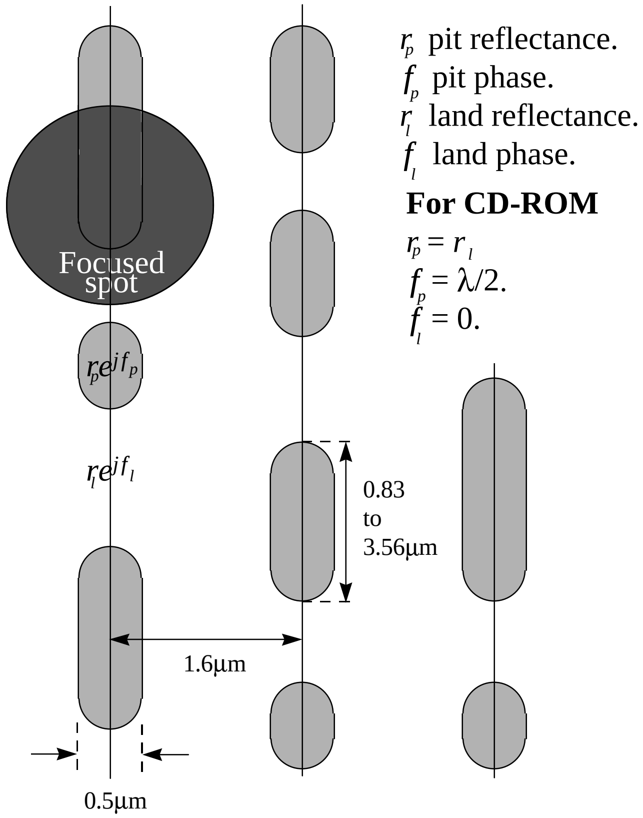


Figure 7.1 : *Pit and track characteristics of the CD-ROM.*

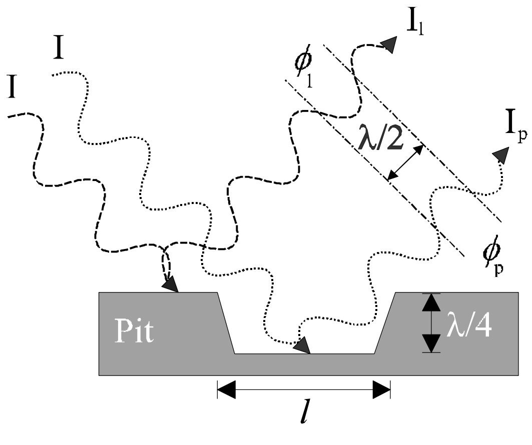


Figure 7.2 : *Interaction of a focused laser beam and the CD pit / land structure.*

During readout a laser beam is focused through the substrate layer of the disc onto the information layer, and is reflected back by the aluminium reflective coating. The purpose of focusing the laser beam through the substrate is to avoid problems such as scratches and dirt on the surface of the substrate interfering with the focused spot.

The depth of the pits is chosen such that any light reflected from within a pit is half a wavelength out of phase with the light reflected from the surrounding areas, the land. Thus, the phase difference between the light reflected from the pits and the light reflected from the land is π, which leads to destructive interference in the reflected beam and a reduction in light intensity is observed, as illustrated in Fig. 7.2 [18,32,77,78,79].

The coding scheme employed in CD-ROM systems, Eight to Fourteen Modulation, or EFM, is used to convert the digital bit stream into a sequence of binary symbols, referred to as channel bits. The EFM coding scheme ensures that any dc content in the data stream is removed and that the run length of sequential like symbols is constrained by the properties of the coding scheme. Hence, the minimum number of 0's between successive 1's is 2, and the maximum number of 0's between successive 1's is 10. Thus, when the data is recorded onto the CD an edge of a pit corresponds to a 1, and elsewhere the code is zero. Hence, it can be seen that the minimum pit length, i.e. the minimum distance between successive 1's, is 3T, where T corresponds to the timing interval of a single bit. The maximum pit length is 11T. These values correspond to the minimum and maximum pit lengths, 0.83μm and 3.56μm respectively [32,80].

Figure 7.3 illustrates the optical head of the CD-ROM replay channel. Comparing this with Fig. 3.1 it can be seen that the optical head of the CD-ROM readout channel is analogous to the readout channel of the Type 1 reflectance scanning microscope, where the objective and collector lenses are one in the same and the coherent illumination is produced by a semiconductor laser.

Since the optical head of the CD-ROM readout channel is analogous to that of the Type 1 reflectance scanning microscope, it is perfectly valid to use the same computational procedures to model the signal generation process in the CD-ROM system. However, in the CD-ROM system the magnitude of reflectance of the information layer does not vary between the land and the pits ($r_p = r_l$). Instead, phase changes are introduced into the reflected field, due to the pits, which leads to destructive interference in the reflected beam ($f_p \neq f_l$). Hence, for a change in phase between land and pits of π an overall change in reflectance for a (re^{jf}) from 1 (from the land) to -1 (from the pit) exists.

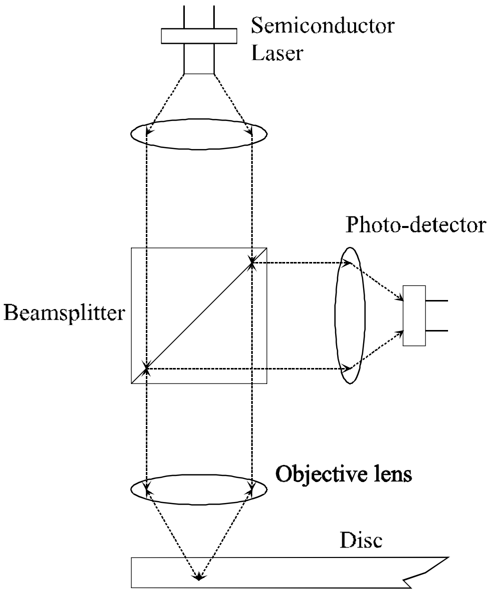


Figure 7.3 : *The optical head of the CD-ROM readout channel (focusing and tracking detectors not illustrated).*

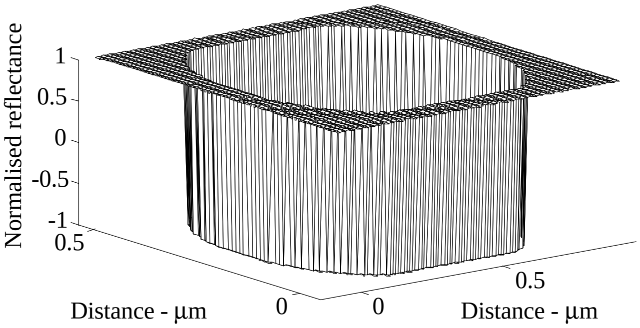


Figure 7.4 : *A simple bit structure used to model the land and pits in the CD-ROM optical system.*

Information held in a CD track can be represented using two-dimensional matrices, the elements of which correspond to the reflectance properties of the disc at sample intervals along the track. Figure 7.4 illustrates a matrix that represents a pit of minimum run-length length 0.83µm, and width 0.5µm. The output response of the CD-ROM readout channel to such a pit, along the centre of a track, can be easily generated from such objects by using the direct calculation approach described in sec. 5.1.

Figure 7.5 illustrates the resulting response of the CD-ROM readout channel to the minimum, 0.83μm - 3T, and maximum, 3.56μm - 11T, pit lengths, with the conditions outlined in table 7.1.

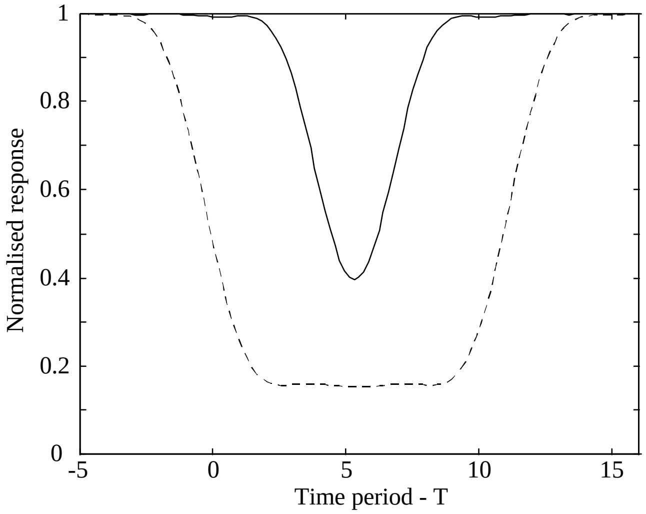


Figure 7.5 : *Response of the CD-ROM system to the minimum and maximum pit lengths, 3T and 11T, generated using the direct calculation approach with the conditions outlined in table 7.1.*

Objective pupil	Circular - radius *a*
Collector pupil	Circular - radius *a*
Incident illumination	Uniform
Wavelength	800nm
NA	0.5

Table 7.1

Using this analysis it is relatively straight forward to investigate the effects due to problems encountered in optical disc systems, such as tracking errors. An additional advantage of this approach is the ability to generate readout waveforms to arbitrary data patterns, by simulating the recorded data on the CD-ROM, and using the direct calculation approach to predict the response of the readout channel. Figure 7.6

illustrates the response of the commercial PD CD-ROM drive [81] to an arbitrary data pattern, also illustrated is the response generated using the direct calculation approach with the conditions outlined in table 7.2.

Objective aperture	circular - radius *a*
Collector aperture	circular - radius *a*
Incident illumination	PD characteristics [81] (*w* - width) radial (across track) *w=2a* tangential (along track) *w=4a*
Wavelength	800nm
NA	0.5

Table 7.2

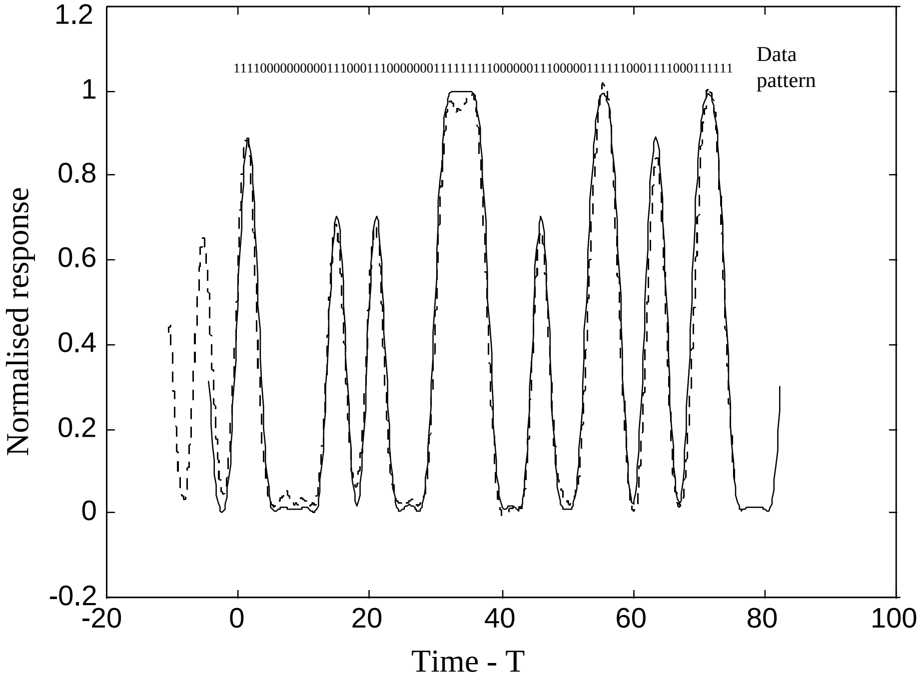


Figure 7.6 : *Plot of CD response obtained from the PD drive (dashed line) and response generated using the direct calculation approach (solid line) with the conditions outlined in table 7.2.*

Comparing the two it can be seen that applying the direct calculation approach for modelling the signal generation process in the CD-ROM system produces results that agree extremely well with experimental signals observed in commercial drives. Hence, it can be assumed that the computational procedures for generating the response from the Type 1 reflectance scanning microscope can be used to predict the response in CD-ROM systems.

7.2.1 The DVD-ROM system

The DVD, or **D**igital **V**ersatile **D**isc, is the latest optical storage technology to enter the market and consists of a family of ROM and RAM optical discs. The DVD-ROM is a read only standard and is similar in design and operation to the CD-ROM. However, the DVD-ROM has a much greater capacity, initially 4.7 Gbytes per disc for a single layer disc, which attained by using smaller pit lengths, minimum 0.4μm, and a shorter track pitch of 0.74μm. Additions to the standard project even greater storage densities, > 10 Gbytes per disc, by using double layer and double sided discs [105].

The optical head of the DVD-ROM replay channel is identical to that of the CD-ROM. Hence, the same mathematical procedure may be used to generate the response of the DVD-ROM.

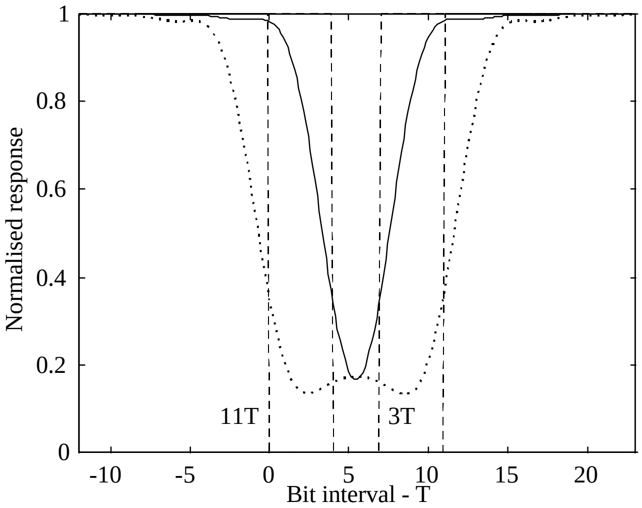


Figure 7.7 : *Response of the DVD-ROM replay channel to the minimum 3T pit length (solid line), profile of pit (dashed line), and to the maximum 11T pit length (dotted line), profile of pit (dashed line), generated using the direct calculation approach, with the conditions outlined in table 7.3.*

Figure 7.7 illustrates the response of the DVD-ROM to the minimum and maximum pit lengths, 3T - 0.83μm and 11T - 3.56μm. The response was generated using the direct calculation approach with the conditions outlined in table 7.3.

Objective aperture	circular - radius *a*
Collector aperture	circular - radius *a*
Incident illumination	DVD-ROM characteristics (*I* - intensity at the rim of the aperture) radial (across track) *I=0.6* tangential (along track) *I=1*
Wavelength	650nm
NA	0.6

Table 7.3

Hence, the usefulness of the direct calculation approach for predicting the readout performance of new storage technologies is clearly demonstrated.

7.3 Phase change optical systems

Phase change optical systems have many advantages over current ROM and WORM storage media. The advantages of phase change media are as follows:

1) erasable
2) the signal generation process is a reflectance change, unlike the CD-ROM system
3) direct overwrite of the memory layer can be easily achieved using laser modulation
4) there is no need for the provision of magnetic fields for writing
5) reflectance changes upon readout - compatibility with current CD-ROM drives.

In phase change media the active layer is subject to crystallographic changes when heated by laser light radiation. Amorphous marks are written into the crystalline layer by short controlled bursts of laser radiation. These amorphous marks have a characteristically low magnitude of reflectance compared with the crystalline surface. On readout a focused low power laser beam is scanned along a track. This beam is reflected from the information layer, the intensity of the reflected field depends upon whether there is a bit present or not, as illustrated in Fig. 7.8.

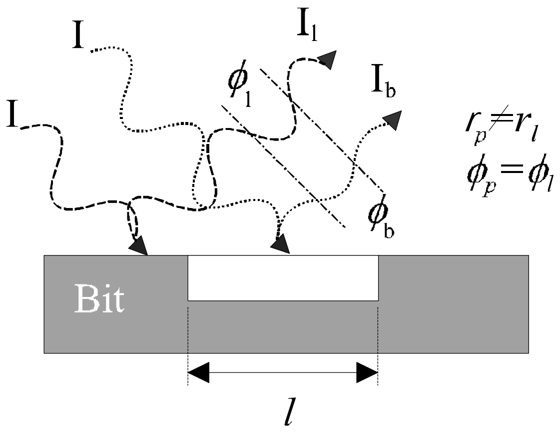


Figure 7.8 : *Interaction of a focused laser beam and the phase change bit structure.*

Many commercial companies are producing phase-change media that are also compatible with current CD technology. The ‘CD-Erasable’ system, produced by Philips, is such a phase change system and the illumination conditions for this system were used to produce the CD-ROM response illustrated in Fig. 7.6.

The optical head of the phase change replay channel is identical to that of the CD-ROM channel illustrated in Fig. 7.2. Hence, it is perfectly valid to use the same computational procedures to model the signal generation process in the phase change system. However, for the phase change system it is the magnitude of the reflectance that varies from pit to land rather than the phase (i.e. $r_p \neq r_l$, $f_p = f_l$).

7.3.1 The DVD-RAM system

In the DVD standard, the format of the discs of the proposed read/write standard, DVD-RAM, is phase change. The surface of the substrate is a land and groove structure, where alternate tracks are recorded in the land and groove. The width of the bits thus depends on the width of the land / groove, which is 0.74μm, so it assumed here that the minimum bit width will be < 0.74μm. The initial storage capacity of the DVD-RAM phase change discs will be less than that of the DVD-

ROM. However, it is assumed that as technology advances the storage capacity will increase. Figure 7.9 illustrates the response of the DVD-RAM replay channel to the minimum and maximum recorded bit structures, 3T - 0.4μm and 11T - 1.47μm. The reflectance of the bit (amorphous) is taken to be 48% and the reflectance of the land (crystalline) is 52%. The response was generated using the direct calculation approach with the conditions outlined in table 7.3.

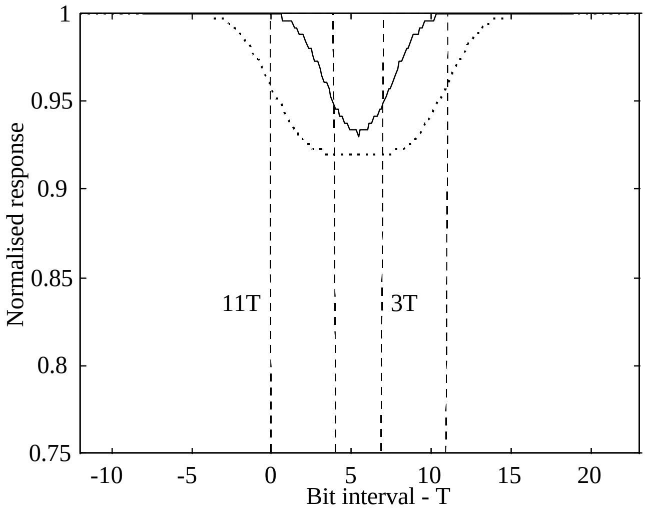


Figure 7.9 : *Response of the DVD-RAM replay channel to the minimum 3T (solid line, profile of bit (dashed line), and to the maximum 11T recorded bit structure (dotted line), profile of bit (dashed line), generated using the direct calculation approach, with the conditions outlined in table 7.3.*

7.3.2 The effect of finite bit width

Figure 7.10 illustrates a simple object which represents a step in reflectance of finite track width. Such a ‘pulse’ can be used to represent a bit structure in a reflectance optical storage system, as in phase change systems.

It is interesting to compare the response to such a simple bit structure with that of the ideal one-dimensional step response illustrated in Fig. 5.3, and also to investigate what effects the end shape of the bit has upon the response.

Figure 7.11 illustrates the response of the Type 1 reflectance scanning microscope to three step objects. A step of infinite width, a bit of finite width λ/NA which has a square end shape, as illustrated in Fig. 7.10, and a bit of finite width λ/NA which has a semicircular end shape. The responses were generated using the transfer function approach with the conditions outlined in table 7.1.

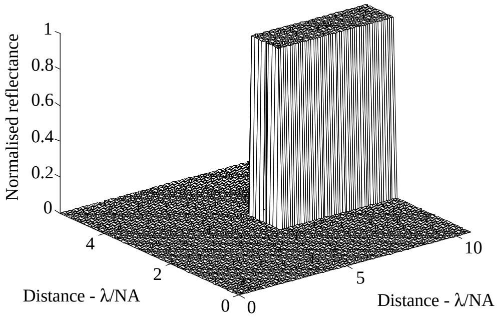


Figure 7.10 : *A simple step in reflectance from 0 to 100% which is of finite track width of l/NA.*

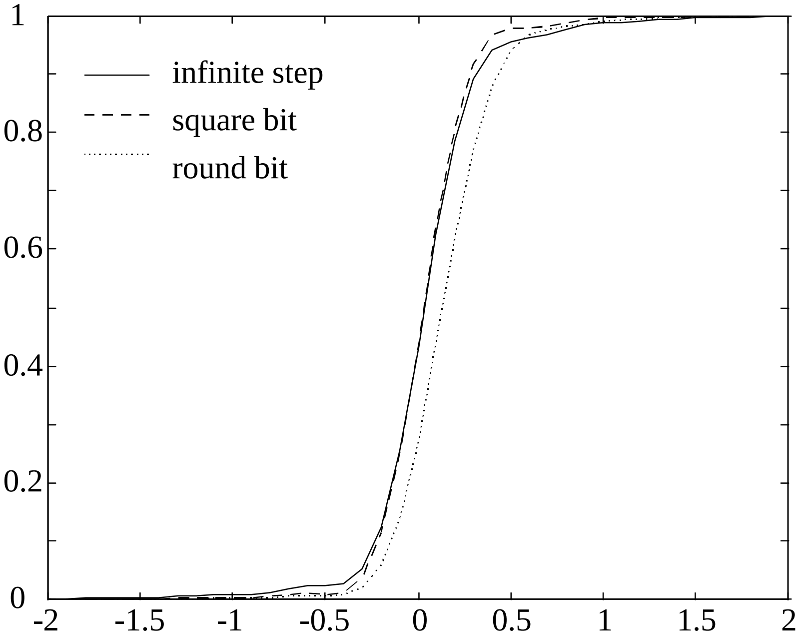


Figure 7.11 : *Normalised response of the Type 1 reflectance scanning microscope to a step of infinite width (solid line), a bit of finite width with a square end shape (dashed line), and a bit of finite width with a semicircular end shape (dotted line).*

Figure 7.11 illustrates that there is very little difference between the responses of an infinite step and of a bit with a square end shape, apart from a dc shift which has been removed from Fig. 7.11. An interesting result is that the response to a bit with a semicircular end shape lags the response of the square bit, by an amount which is approximately 0.1λ/NA. Such differences have important consequences for the design of data recovery sub-systems in optical storage disc drives.

7.4 Magneto-optic systems

The magneto-optical optical disc system was released onto the market in the late 1980s, as an alternative read/write storage media to magnetic storage and optical WORM systems.

Early magneto-optic systems used pulse position modulation, PPM, recording, where the data is recorded as a magnetic domain, and the RLL (2,7) coding scheme, to give a bit density of approximately 0.4Gbit/in^2 [78,83]. Commercial MO drives by companies such as IBM, Hewlett-Packard and Sony have a capacity of between 325 and 650Mbytes per side on a 130mm disc.

More modern MO drives use pulse width modulation, PWM, recording, where data is recorded in the edge of bits, and the RLL (1,7) coding scheme is used giving bit densities >0.85Gbit/in^2, the ISO-MO standard [82]. Currently mark lengths of 0.49μm at a track pitch 1.15μm are attainable, giving a storage density of 1.15Gbit/in^2, using a laser wavelength of 680nm and an NA of 0.5. Researchers are claiming even greater storage densities [83]. Hence, it can be seen that magneto-optic disc storage systems are a viable alternative to current storage technologies for attaining high data density on removable media.

The physical principles of magneto-optical replay have been presented in detail previously. Hence, they will not be discussed in the following analysis.

Figure 7.12 illustrates the optical head of the MO replay channel.

Comparing Fig. 7.12 with Fig. 4.3 it can be seen that the optical head of the MO readout channel is analogous to that of the Type 1 differential detector MO scanning microscope, where the objective and collector lenses are one in the same and the coherent illumination is produced by a semiconductor laser.

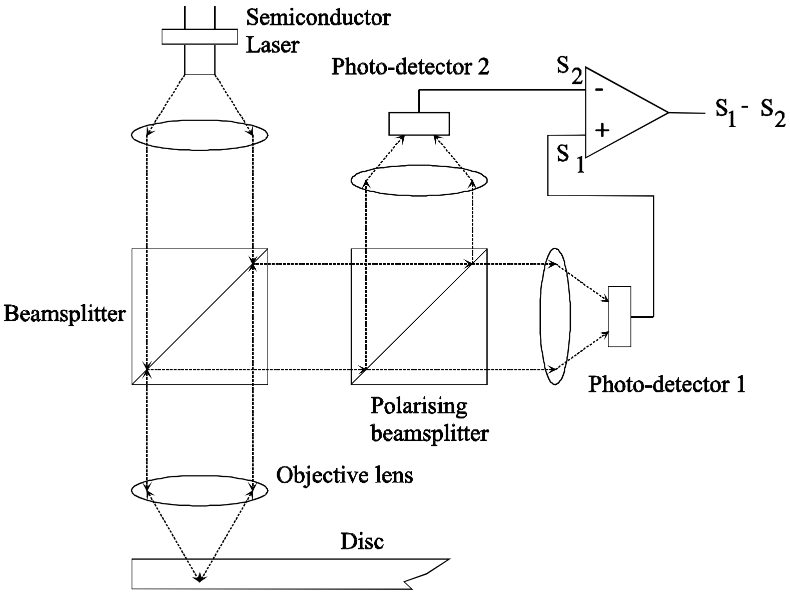


Figure 7.12 : *The optical head of the MO readout channel (focusing and tracking detectors not illustrated).*

Since the optical head of the MO readout channel is analogous to that of the Type 1 differential detector scanning microscope, it is perfectly valid to use the same computational procedures to model the signal generation process in the MO disc system.

Information held in a track can be represented using two-dimensional matrices, the elements of which correspond to the MO properties of the disc at sample intervals along the track. The output response from the MO readout channel can be easily generated by using the direct calculation algorithm to calculate the signal generated by scanning along the centre of the track.

Figure 7.13 illustrates three MO bit profiles generated using a magneto-optic recording model [84]. The bits have been generated in the MATLAB software environment for a variety of write compensation techniques and simulate the recording of magnetic domains in a 6 layer (glass/dielectric/TbFeCo/dielectric/Al/Glass) disc structure.

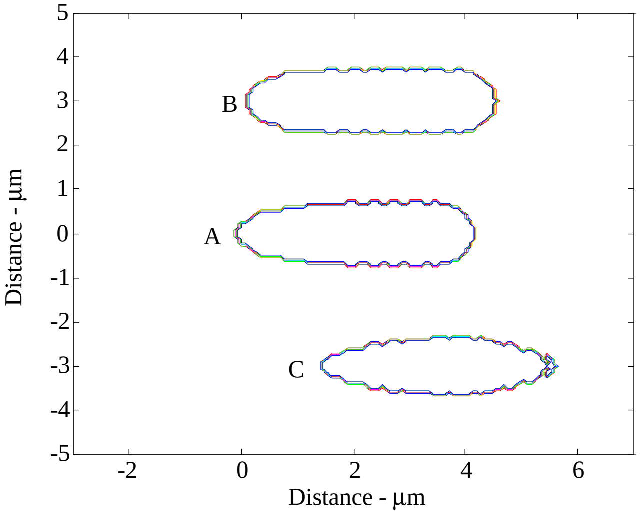


Figure 7.13 : *Recorded domain boundaries written using write laser modulation techniques.*

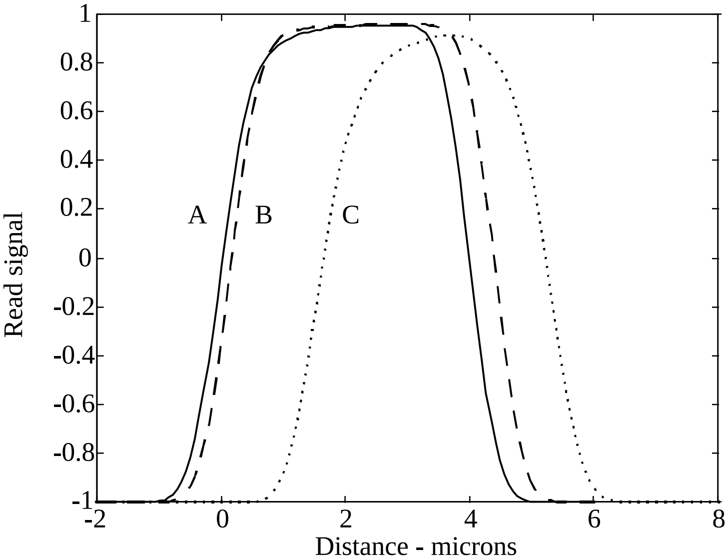


Figure 7.14 : *The response of the MO readout channel to the bit structures illustrated in Fig. 7.13, generated using the direct calculation approach with the conditions outlined in table 7.4.*

Figure 7.14 illustrates the response of the MO readout channel to these simple bit structures. The responses were generated using the direct calculation approach with the conditions outlined in table 7.4, for a MO sample of uniform ordinary reflectance (r_x equal to unity) and zero phase [85,88].

Objective aperture	circular - radius *a*
Collector aperture	circular - radius *a*
Incident illumination	(*w* - width) radial (across track) *w=2a* tangential (along track) *w=4a*
Wavelength	800nm [85,88]
NA	0.5

Table 7.4

The direct calculation approach can be used to investigate aspects of readout in commercial MO disc systems, such as the effects of tracking errors on the response of the readout channel, as illustrated in Fig. 5.15 and Fig. 5.16.

7.4.1 The effect of finite bit width

Figure 7.15 illustrates the response of the Type 1 differential detector MO scanning microscope to bit structures of finite width similar to those discussed in sec. 7.3.2. The responses were generated using the direct calculation algorithm, with the conditions outlined in table 7.1, for a MO sample of uniform ordinary reflectance (r_x equal to unity) and zero phase. Also illustrated is a plot of a response to a similar bit structure extracted from published data [74].

The theoretical responses illustrated in Fig. 7.15 have been generated for a step in MO Kerr rotation from -0.5° to +0.5°. The published result illustrated in Fig. 7.15 (circles) has been generated using a vector diffraction approach to modelling the MO channel [60,74,75,76].

Comparing the theoretical response (solid line) and the published response (circles) in Fig. 7.15, it can be seen that the two very different approaches to modelling the MO read channel produce exactly the same results. Again it is evident from Fig. 7.15 that the response to a bit with a semicircular edge shape is shifted with respect to that of the square end shape, which can be measured to be approximately 0.1λ/NA.

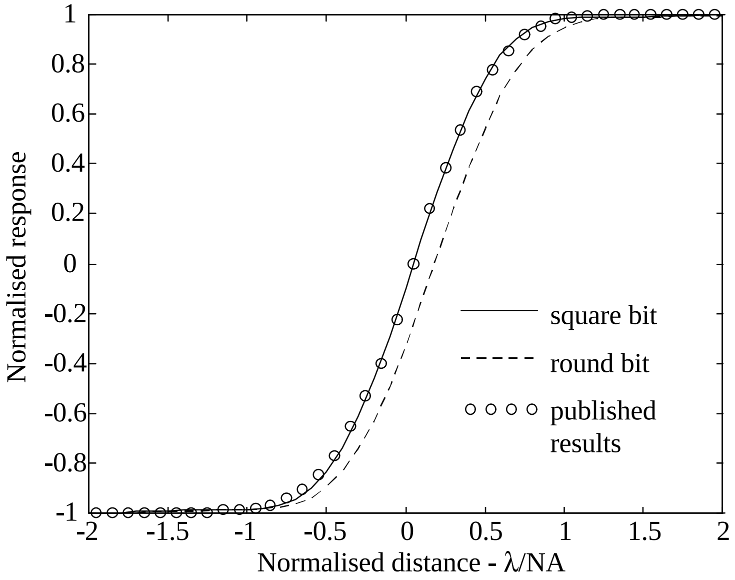


Figure 7.15 : *Normalised response of the Type 1differential detector MO scanning microscope to a bit of finite width with a square end shape (solid line), and a bit of finite width with a semicircular end shape (dashed line). Also illustrated is the response to a similar bit structure extracted from a published paper (circles).*

7.5 Analysis of channel optimisation techniques

In the following section techniques for modifying the spatial frequency characteristics of the PCTF, and hence the imaging system, are described in detail.

In the conventional scanning microscope, Type 1 or confocal, the optical resolution is determined primarily by the size of the diffraction limited focused spot, which is a function of the wavelength of illumination (λ) and numerical aperture (NA) of the objective lens. The cut-off spatial frequency of the conventional optical system is, as shown previously, given by twice the numerical aperture of the objective lens divided by the wavelength of illumination. Hence, an obvious method to increase the resolution of the optical system is to increase the NA of the objective lens and reduce the wavelength of the incident illumination. The NA in current optical storage systems is typically in the range 0.45 to 0.55, with 0.6 NA objectives being proposed for DVD systems. However, it is hard to imagine that the NA will increase any further due to the dependence on the NA of the depth of focus, and hence the tolerances of the focus system. As for the wavelength of illumination, current values are typically in the range 780nm to 830nmn with 650nm being proposed for DVD systems. However, the limitations of current technology prevents solid state lasers being produced which operate reliably at lower wavelengths. Hence, the limits for the objective NA and incident wavelength are currently being reached [20,94].

An alternative approach that may be used to modify the imaging properties of the scanning microscope is by the use of optical filtering [54,83] . Two terms can be used to describe this filtering process, ‘super-resolution’ and ‘apodization’. Super-resolution is primarily concerned with the improvement of the spatial frequency response near to the resolution limit, and is a form of high-pass filtering. Apodization is primarily concerned with the removal of undesirable sidelobes in the focused spot and may be viewed as a form of low-pass filtering. Apodization is commonly used to remove the effects of ringing in the response of the coherent imaging system [89,90,91,92,93]. However, in the current analysis the terms ‘super-resolution’ and ‘apodization’ will be used interchangeably to describe any optical filtering technique performed in the optical path of the scanning microscope.

Yamanaka et al. have demonstrated that optical filtering can be used to reduce the size of the focused spot. Their proposed method involves placing a shading band filter in the illumination path, which results in a multi-lobed focused spot, the central lobe of which is narrower than without the filter [94]. Milster et al. have demonstrated that placing a shading band filter in the collector path of a MO data storage device can be used to modify the imaging characteristics of the replay channel to give more desirable results [38]. Ando et al. have demonstrated that placing an annular phase-shifting apodizer in the objective / collector path of an optical storage device increases the readout resolution of the readout signal whilst reducing the error rate, leading to greater recording densities [95].

Thus, super-resolution has many uses in optical imaging systems. In the following section some simple optical filtering techniques are presented, and their effects upon the spatial frequency response of the PCTF described.

An alternative use for super-resolution techniques is to modify the spatial frequency characteristics of the replay channel to suit a desired response : channel optimisation. Such a technique will be described for optimising the replay channel of the MO optical head to that of so called partial response (PR) class 1 signalling [82,83,96,98,101,103].

7.5.1 Super-resolution techniques

A simple way to modify the response of the optical replay channel is to modify the profile of the incident illumination characteristics. The profile of the incident illumination from a laser is typically Gaussian in shape. In previous chapters the effects of changing the profile of the incident illumination from Gaussian to uniform upon the response of the scanning microscopes have been illustrated. In Fig. 7.16 the shape of the normalised Type 1 PCTF is illustrated, along the n_x axis, for varying widths of incident Gaussian illumination, $w_{e^{-2}}$ vs. a. It can be seen that varying the width of the incident Gaussian illumination, with respect to the radius of the objective aperture, can have a great effect upon the spatial frequency response of the Type 1 scanning microscope. Uniform incident illumination (effectively the solid line in Fig. 7.16) produces the smallest focused spot, i.e. the Airy disc for a clear, aberration free, circular objective aperture. However, as the profile of the incident illumination is changed to a Gaussian distribution, effectively narrowing the field of illumination, then the resulting focused spot will broaden. This leads to a reduction in resolution and hence, a reduction in the effective cut-off spatial frequency of the imaging system.

It should be noted that the case of uniform illumination produces an upper bound to the spatial frequency response. Any modification of the spatial frequency response, due to optical filtering or incident illumination shaping, will reduce the magnitude of the PCTF which will lead to a reduction of the light transmitted through the optical system, and hence, the signal from the photo-detector.

Placing optical filters, or obscurations, in the objective path will effectively reduce the amount of light incident on the sample and change the profile of the focused spot. In the scanning microscope this may not be a problem. However, in optical disc systems, especially read/write systems, it is important to maintain high power levels at the sample surface and to maintain a regularly shaped spot profile, otherwise the recording ability may be impaired. Hence, it is important for storage applications that the objective path remains unobscured, and any optical filtering should be performed in the collector arm of the imaging system.

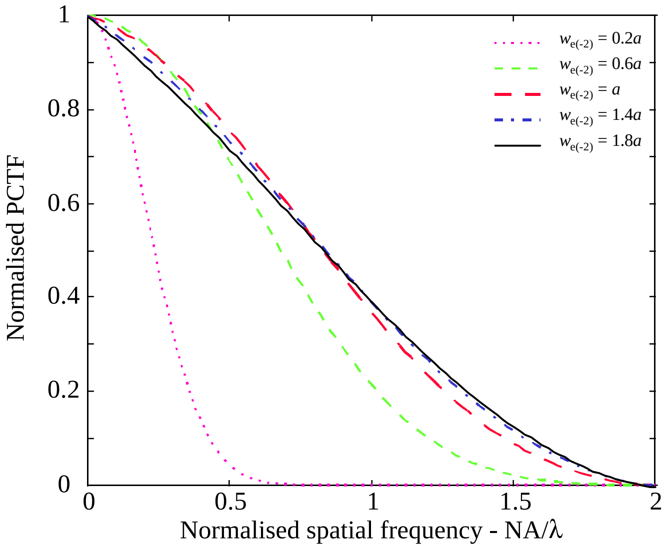


Figure 7.16 : *Plot along the n_x axis of the Type 1 PCTF for varying widths of Gaussian incident illumination.*

In a collimated optical system, any obscuration placed in the objective or collector optical path can be modelled as a modification of the corresponding aperture pupil function. Figure 7.17 illustrates the formulation of a matrix representing the modified aperture pupil function, by the array multiplication of a matrix representing a circular aperture pupil function, of radius a, and a matrix representing a clear rectangular obscuration, of width a.

The PCTF can thus be calculated for an apodized system using the procedures described in sec. 6.1, where the aperture pupil functions are modified to take into account the obscurations placed in the objective / collector optical path.

In the following sections the imaging characteristics of the Type 1 scanning microscopes employing rectangular shading bands and annular obscurations in the collector optical path are investigated.

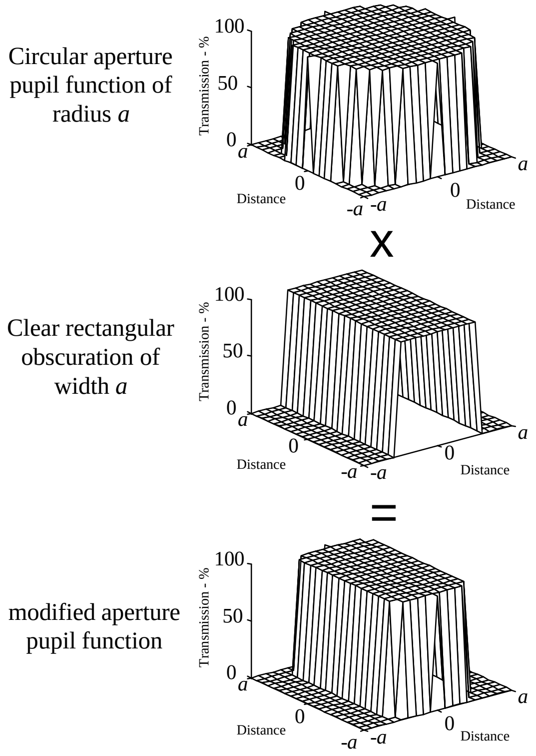


Figure 7.17 : *The formulation of the modified aperture pupil function.*

Apodization using rectangular shading bands

Figure 7.18 illustrates a matrix representing a circular aperture pupil function employing a clear rectangular shading band. Areas with 100% transmission coefficient transmit all the incident light, whereas areas with 0% transmission coefficient block the incident light.

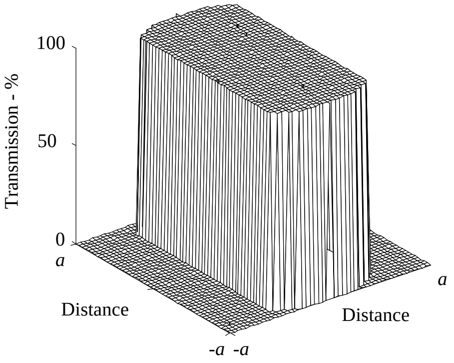


Figure 7.18 : *The circular aperture pupil function, of radius a, employing a clear rectangular shading band, of width a.*

Objective aperture	Circular - radius *a*
Collector aperture	Circular - radius *a*
Illumination	Uniform

Table 7.5

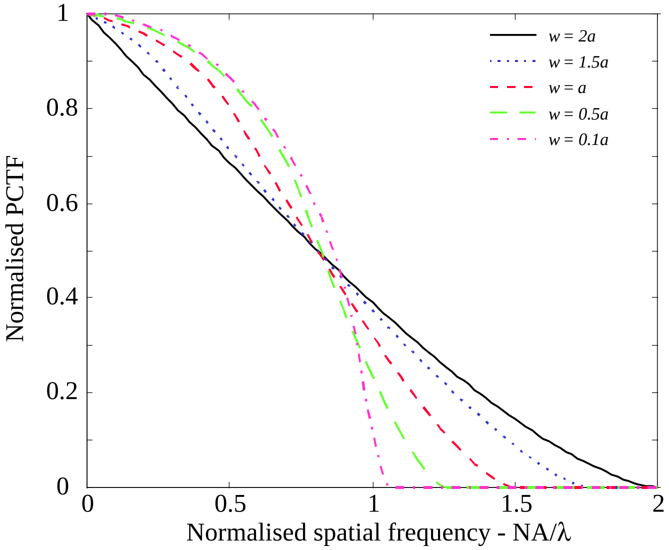


Figure 7.19 : *Plot along the* n_x *axis of the Type 1 PCTF for a clear rectangular shading band, of varying width w, placed in the collector optical path.*

Figure 7.19 illustrates the form of the Type 1 PCTF along the n_x axis, for a clear vertical rectangular shading band, of varying width, placed in the collector optical path. The PCTF was generated using the algorithm presented in sec. 6.1.1, with the conditions outlined in table 7.5. It is apparent that placing a clear rectangular shading band in the collector optical path reduces the spatial frequency cut-off of the optical system. However, the low spatial frequency components are boosted with respect to the high spatial frequency components.

Figure 7.20 illustrates a matrix representing a circular aperture pupil function employing an obscured rectangular shading band. The resulting PCTF is shown in Fig. 7.21. For this case the cut-off spatial frequency remains constant at 2NA/λ. Also, the magnitude of the PCTF becomes constant over a central region as the width of the obscured shading band is increased.

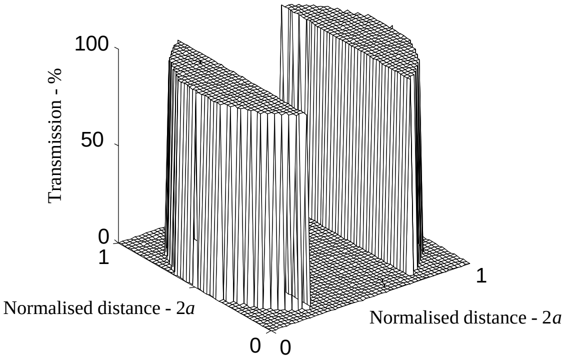


Figure 7.20 : *The circular aperture pupil function, of radius a, employing a obscured rectangular shading band, of width a.*

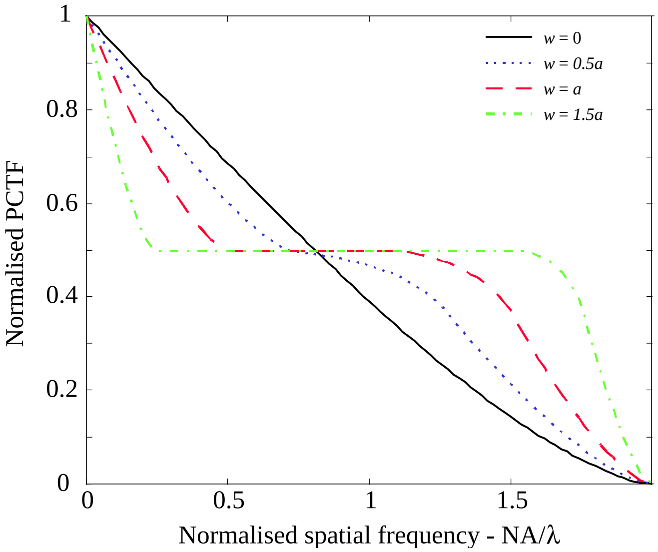


Figure 7.21 : *Plot along the* n_x *axis of the Type 1 PCTF for a obscured rectangular shading band, of varying width, placed in the collector optical path.*

Figure 7.22 illustrates how the spatial frequency response of the Type 1 system can be optimised to resemble that of a pass-band electrical filter using a vertical obscured rectangular shading band, of width 80% the diameter of the circular collector aperture, in the collector optical path, and a clear, aberration free, circular objective under Gaussian ($w_{e^{-2}} = a/2$) incident illumination.

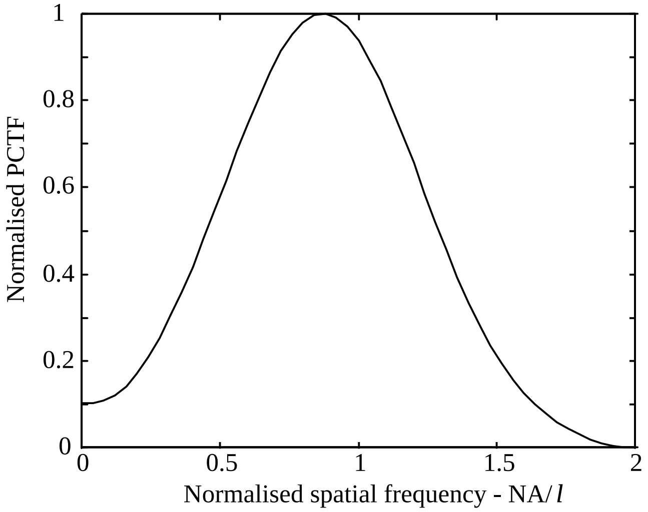


Figure 7.22 : *Plot along the n_x axis of the Type 1 PCTF for an optimised optical channel with a circular objective pupil function under Gaussian ($w_{e^{-2}} = a / 2$) incident illumination and a vertical obscured rectangular shading band (80% the pupil diameter)placed in the circular collector pupil function.*

Apodisation using annular apertures

Figure 7.23 illustrates a matrix representing a circular aperture pupil function employing a annular obscuration. The annulus is one of the most common optical filters used to modify the properties of the imaging system, and is used extensively in coherent imaging systems [47].

Figure 7.24 illustrates the form of the Type 1 PCTF along the n_x axis, for a annular apodizer, of varying inner radius, placed in the collector optical path. The PCTF was generated using the algorithm presented in sec. 6.1.1, using the conditions outlined in table 7.5. It can be seen that the introduction of an annular aperture can be used to improve the high spatial frequency response of the optical system, with respect to the low frequency response.

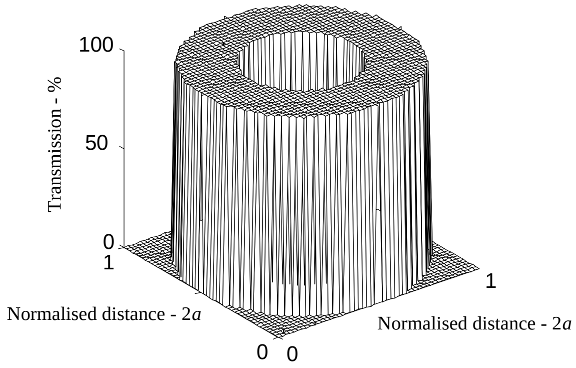


Figure 7.23 : *The circular aperture pupil function, of radius a, employing an annular obsucuration, of outer radius equal to the radius of the circular aperture* $(r_o=a)$ *and an inner annulus radius of half the radius of the circular aperture* $(r_i=a/2)$.

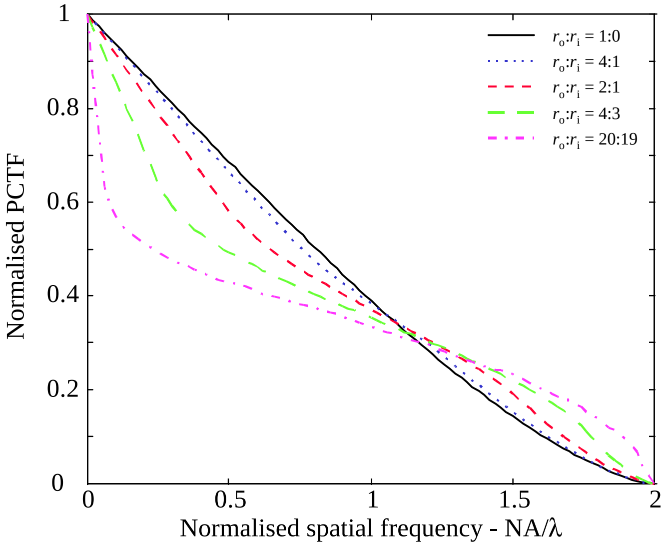


Figure 7.24 : *Plot along the* n_x *axis of the Type 1 PCTF for varying widths of an annulus placed in the collector aperture pupil function.*

7.5.2 Optical equalisation - partial response signalling

To improve the recording density in optical storage systems, it is necessary to improve the resolution of the imaging system. However, as already discussed, conventional options to improve the resolution limit of the optical system, i.e. increase the NA of the objective lens or reduce the wavelength of illumination, are currently limited. Thus, as the data is physically packed closer together on the disc the effects of inter-symbol interference (ISI), where the signals due to neighbouring bits interfere during the readout process, will introduce errors in the data detection process.

Modulation codes have been used effectively in optical disc systems to reduce ISI by maintaining relatively large separations between data pulses, for example the RLL (*n*, *k*) codes. Alternative signal processing techniques introduce controlled amounts of ISI and use special electronic filtering techniques to reconstruct the recorded signal upon replay. This is commonly called partial response (PR) signalling and has been adopted in communication systems for many years and is now also firmly established in magnetic data storage systems [74,83,97,98,99,100]. However, it is only recently that PR signalling has been considered for improving the data storage density in optical systems, especially MO systems [74,82,83,96,101,102,103,104].

Figure 7.25 illustrates how PR equalisation is conventionally implemented in an optical storage system. A novel approach developed as a result of the work of this thesis is to perform the PR equalisation in the optical domain by using appropriate apodisation techniques.

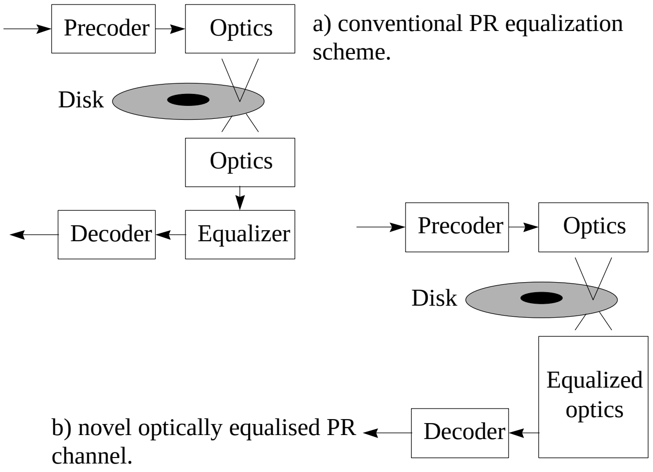


Figure 7.25 : *Conventional PR equalisation and proposed optical equalisation.*

The detailed analysis and description of PR signalling is a wide subject area covered in both communications and data storage applications, and hence is beyond the scope of this thesis. The goal instead is to introduce optical filtering as a means of modifying the transmission characteristics of the MO channel to match that of a particular PR channel characteristic. Optical equalisation is performed by inserting appropriately designed apertures into the optical path. The aim of introducing optical equalisation is to remove the necessity for electronic equalisation upon readout from the optical system, thus improving the SNR of the readout signal. Figure 7.25 illustrates the proposed optical equalisation scheme.

The chosen form of equalisation is that of PR Class 1, or PR(11) [82,83,96,98,101,103]. The channel characteristics of PR class 1 closely resembles that of the axial spatial frequency response of the Type 1 PCTF. The frequency response of the PR Class 1 channel is given by [101]

$$F(D) = (1 + D)\Big|_{D=-\exp\{-jwT\}} \tag{7.7}$$

where T is the bit period and D is the delay operator. Thus, the frequency response of the PR Class 1 channel is given by [98]

$$\left|F(f)\right| = 2\left|\cos\frac{wT}{2}\right| \quad . \tag{7.8}$$

Figure 7.26 illustrates the frequency response of the PR Class 1 system.

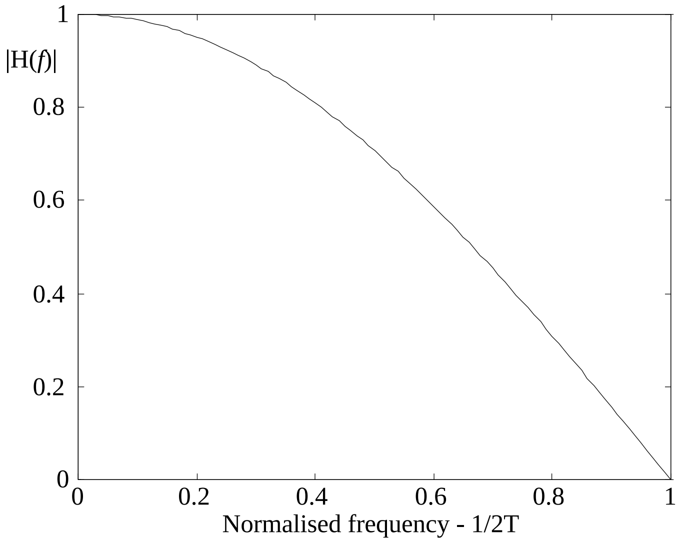
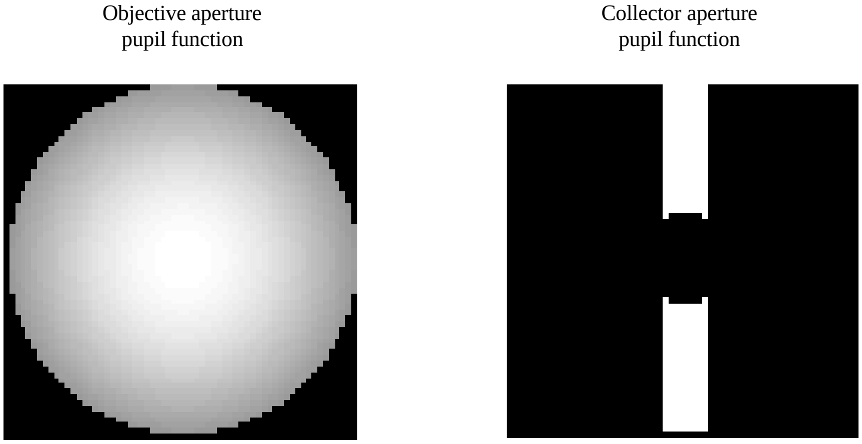


Figure 7.26 : *The frequency response of the PR Class 1 system.*

As an example, it has been chosen to equalise the optical channel such that the bit period, T, corresponds to ul/2NA, where u is the disc velocity. Hence, the spatial frequency cut-off of the equalised optical channel is NA/l. The characteristic cut-off spatial frequency of the optical channel is given by 2NA/l and so the cut-off frequency response of the optical channel needs to be reduced. It has been illustrated previously, in Figs. 7.16, 7.19, 7.21 and 7.24 that modifying the illumination characteristics and introducing optical filters into the collector aperture can modify the response of the Type 1 optical system. Figure 7.27 illustrates the proposed illumination conditions and collector optical filtering to modify the spatial frequency characteristics of the MO readout channel to that of PR Class 1 for a bit length of l/2NA, without the need for electronic equalisation.



Circular aperture of radius a under Gaussian illumination with e^{-2} width parameter of 1.4a

Annular aperture of outer radius a and inner radius 0.25a with a vertical clear shading band of width 0.24a

Figure 7.27 : *Chosen form of incident illumination and obscuration in the collector path, to modify the form of the PCTF to match closely the response of the PR Class 1 channel.*

Figure 7.28 illustrates the spatial frequency characteristics of the optically equalised readout channel.

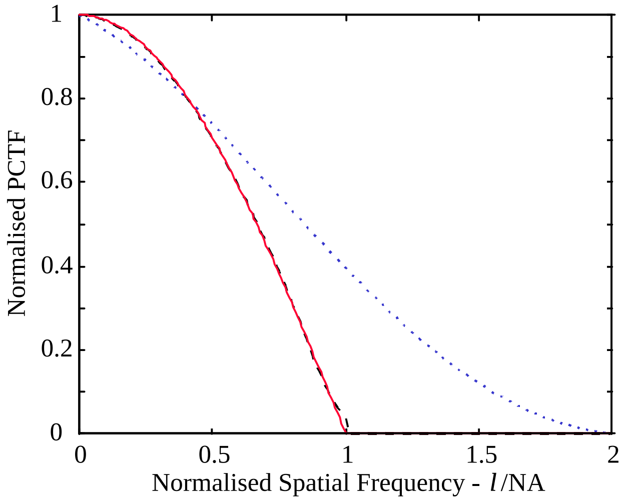


Figure 7.28 : *The spatial frequency response of the optically equalised readout channel (dashed line), the unmodified channel characteristics (dotted line) and the frequency response of the PR Class 1 channel (solid line).*

Using the direct calculation approach it is possible to calculate the response in the time domain of the optically equalised MO channel to a pulse of period T. If the channel has been equalised precisely then the resulting response should equal that of the PR Class 1 channel, as given by the inverse Fourier transform of eq. (7.7), i.e.[98]

$$h(t) = \frac{4T^2}{p} \frac{\cos\left(pt/T\right)}{T^2 - 4t^2} \quad . \tag{7.9}$$

Figure 7.29 illustrates the calculated response of the optically equalised MO channel to a bit of period T as compared to the theoretical pulse response of eq. (7.7). At the crucial sample points, T, the response of the modified optical channel exactly matches the response of the ideal Class 1 PR channel. Thus, it is clear that the optical channel has been successfully equalised to that of the desired PR characteristic, thus removing the necessity for further electronic equalisation.

An obvious disadvantage with the optical equalisation approach is that, due to the obscuration in the collector aperture, the amount of light propagating through to the detector is reduced, thus reducing the signal magnitude from the detector. An obvious advantage however, is that the electronic equalisation has been removed, thus eliminating additional electronic noise invariably introduced in the conventional electronic equalisation process.

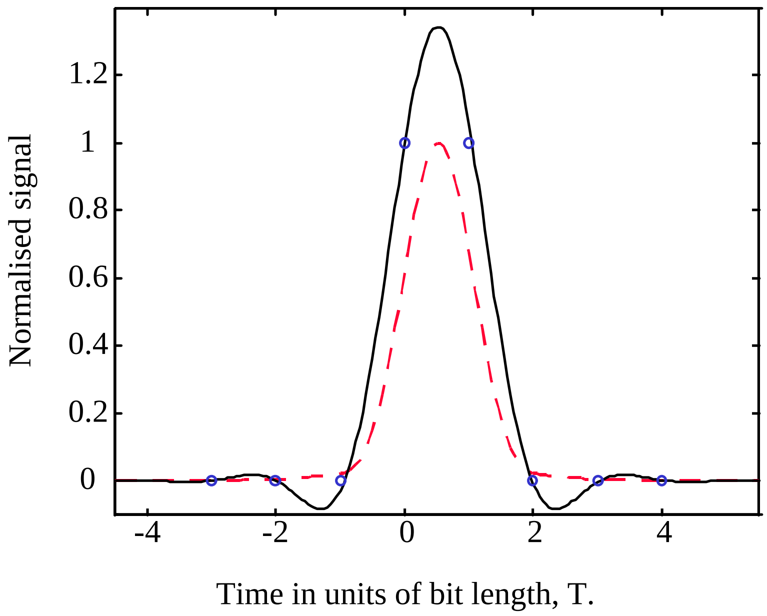


Figure 7.29 : *The response of the optically equalised MO channel to a bit of width T (solid line), the response of the un-equalised optical channel (dashed line), and the response of the PR Class 1 channel at periods of T (circles).*

Thus, it has been illustrated that optical filtering can be used in a variety of ways to modify the channel characteristics of the optical readout channel. Optical equalisation has been presented as a means to modify the optical channel to that of PR Class 1 such that the data density of the optical storage system may be increased.