

Optical Focusing System and Method

FIELD OF INVENTION

The present invention relates broadly to optical focusing system and method, and to applications thereof.

BACKGROUND

A blue laser optical disk has a recording density of not less than 23 GB and a data transfer rate as high as 36 Mbps. However, there is an ongoing need to further increase the recording density, and enhance the data transfer rate.

Use of a phase type binary optical element has been proposed for super-resolution imaging and high density optical data storage. US patent No. 5349592, (Hideo Ando) describes the use of a binary apodizer in a compact disk (CD) system to obtain super-resolution reading. However, it is difficult to use this kind of device in a blue laser disk system to get a super-resolution focused spot, because of the very strong longitudinal field component in the focused circular polarized beam. Also, the intensity of side lobes around the focused spot would be much higher compared to a CD system.

US patent No. 5496995 describes super-resolution scanning optical devices, which use binary phase optical elements in either reflection or transmission mode with the purpose of minimizing the focused spot without remarkably decreasing the intensity of the main lobe.

European patent No. 0831471 describes the use of both two level and multi-level phase optical elements in the optical head of a CD and a digital video disc (DVD) systems to minimize the focused spot for reading and writing.

Chinese patent ZL 00127615.8 and the Journal Paper ["High focal depth with a pure-phase apodizer," Haifeng Wang and Fuxi Gan, Applied Optics, Vol. 40, No.31, 5658-5622, 2001] describe the use of a binary phase element to achieve super-resolution and at the same time obtain uniform axial intensity distribution where both the transversal and the axial field distribution were taken into account.

It is difficult to apply the techniques in the above mentioned documents to blue laser disk systems, because with high numerical aperture focusing systems, very little super-resolution effect can be achieved and the side lobe of the focused spot is much higher, which is the result of the strong longitudinal field component. It is also a technical challenge to reduce the spherical aberration, increase the margin of thickness variation and achieve larger working distance in high density optical recording. Furthermore, for high numerical aperture focusing systems, the focus spot size when introducing an apodizer will always be larger than without the apodizer due to the cross polarization effect.

A need therefore exists to provide a system and method that seek to address at least one of the above-mentioned problems.

SUMMARY

In accordance with a first aspect of the present invention there is provided an optical focusing system comprising an optical beam shaper for shaping an incoming laser beam into a radial symmetric beam; a polarization modulator disposed such that the radial symmetric beam is a radial polarized beam; and a lens element for focusing the radial polarized beam at a focal plane.

The system may further comprise an apodizer element for introducing a Pi phase difference between different belts of the radial polarized beam such that light from the different belts interferes at the focal plane.

The system may further comprise an optical element for forming an annular beam from the radial symmetric beam.

The polarization modulator may be disposed before the optical element or after the optical element along an optical path of the system.

The optical element may be formed integral with the apodizer element.

The system may further comprise a beam splitter for splitting a reading beam from the radial polarized beam in reflection from the focal plane.

The system may further comprise a lens unit for focusing the reading beam.

5 The system may further comprise a photo detector for detecting the focused reading beam.

The system may further comprise a CCD unit for performing imaging from the focused reading beam.

10 The beam splitter may be formed integral with the beam shaper.

The system may be configured in one of a group consisting of an optical disk system, a scanning system, a confocal imaging system, a three dimensional imaging system, a lithography system, an alignment system, an optical tweezer, and a particle
15 acceleration system.

In accordance with a second aspect of the present invention there is provided method of optical focusing, the method comprising the steps of shaping an incoming laser beam into a radial symmetric beam; polarizing the radial symmetric beam into
20 a radial polarized beam; and focusing the radial polarized beam at a focal plane.

BRIEF DESCRIPTION OF THE DRAWINGS

25 Embodiments of the invention will be better understood and readily apparent to one of ordinary skill in the art from the following written description, by way of example only, and in conjunction with the drawings, in which:

Fig. 1 is a schematic diagram showing a design to obtain a super-resolution focused beam for a high numerical aperture focusing system according to an
30 embodiment of the invention, which can provide both high resolution and long depth of focus. The polarization modulator is composed of four pieces of half wave plates with slow axis in different directions.

Fig. 2 is a schematic diagram showing a design using a center obstruction phase mask and a polarization modulator to obtain a super-resolution focused beam for a high

numerical aperture focusing system according to another embodiment, which can provide both high resolution and long depth of focus.

Fig. 3 is a schematic diagram showing a design using an annular beam shaper and a polarization modulator to obtain a super-resolution focused beam for a high numerical aperture focusing system according to another embodiment, which can provide both high resolution and long depth of focus.

Fig. 4 a schematic diagram showing a design using a binary phase mask and a polarization modulator to obtain a super-resolution focused beam for a high numerical aperture focusing system according to another embodiments which can provide both high resolution and long depth of focus for biological imaging.

Fig. 5 shows an intensity image and longitudinal field component phase contour plot in the X-Z cross-section of the focused beam.

Fig. 6 shows an axial intensity distribution.

Fig. 7 shows a radial intensity distribution; the maximum side lobe intensity is about 16%.

Fig. 8 is an alternative annular beam shaper for use in different embodiments of the present invention.

Fig. 9 shows a flow chart illustrating a method of optical focusing according to an example embodiment.

DETAILED DESCRIPTION

Optical data storage systems are proposed described in the example embodiments which use a phase or amplitude apodizer, polarization modulator and a multi-level recording method. In the example embodiments, the focusing spot size is as small as 0.43λ , which corresponds to a disk capacity of 23.8GB and 61.7GB for red light and blue light, respectively. The focused spot size is almost invariable within a relatively large region. The long depth of field also makes it easier for a track and serving system to follow the vibration of the disk. The data transfer rate could also be further increased by increasing the rotation speed. The example embodiments can also find applications in laser machining, metrology and optical alignment systems, three dimensional imaging, optical coherent tomography, lithography and scanning microscopy etc.

The example embodiments relate to fourth generation data storage, three dimensional imaging, lithography and scanning microscopy, optical alignment system,

optical coherent tomography. In particular, the example embodiments can provide a data storage device that can achieve higher density and have longer depth of focus. With longer focal depth, the servo can follow the fluctuation more easily, the optical drive can be more silent because the pickup head does not have to follow the higher frequency vibration of the disk, and the almost equal intensity distribution within the focal region may allow to have a better control over the reading/writing power, and the writing mark length. The data transfer rate can also be increased by increasing the rotation speed.

A blue laser disk uses a laser wavelength of 405 nm and an objective lens with a numerical aperture of 0.85. It is quite difficult to further minimize the recording light spot through conventional techniques such as increasing the numerical aperture of the lens or reducing the laser wavelength. All the drives of CD, DVD and blue laser disks work in the far field, which makes it easier for a drive to read all kinds of disks. The example embodiments provide an approach to minimize the focused light spot in the far field, and to make it easier for the optical head to do the servo.

As is shown in Fig. 1 one example embodiment comprises a laser beam 100 from a laser diode (LD) 102 being collimated by a lens 104 and shaped by a prism 105 into a circular symmetric beam 101. The circular laser beam 101 is turned into an annular beam 106 by an annular beam shaper 108. The lower spatial frequency light is thus shifted to higher spatial frequency belt, which can reduce the spot size after being focused by the lens 118. After passing through a beam splitter 110, the annular beam 106 is modulated by a polarization modulator 112 and changed into a radial polarized annular beam 114. This radial polarized annular beam 114 is advantageously used for a high numerical aperture focusing lens 118, which can reduce the cross polarization effect in this example embodiment.

The radial polarized annular beam 114 then passes through an apodizer 116 to modulate its phase, and is focused by the high numerical aperture lens (NA=0.95) 118 onto the plane 120 of an optical disk 122. The light from the inner belt 117 of the apodizer 116 has a π phase difference to the light from the outer belt 119 of the apodizer. The corresponding belts of the phase modulated radial polarised annular beam 115 interfere in the focal plane 120, which further reduces the spot size and makes the light intensity uniform along the optical axis. The reading and writing process is the same as for a conventional blue laser disk, with a lens system for the reading beam 125, in reflection from the disk 122, consisting of a focusing lens 124 and

cylindrical lens 126 for reducing the focusing error for the objective lens and detecting the read signal at a photo detector 128.

The full width half maximum of the focused light spot at the plane 120 of the optical disk 122 is 0.43λ , as is shown in Fig. 5. For blue or red light sources, the spot size and the achievable capacity in this embodiment are shown in Table 1 under the disk types "Super-Blue" and "Super-Red" respectively, compound with existing systems.

Table 1

Disk type	DVD	HD DVD	Blue laser Disk	Super-Red	Super-Blue
NA	0.65	0.65	0.85	0.95	0.95
wavelength	0.65	0.405	0.405	0.65	0.405
Polarization state	Circular	Circular	Circular	Radial	Radial
Spot size (FWHM) (micron)	0.533	0.332	0.263	0.280	0.174
Spot area (FWHM) ²	0.2841	0.1102	0.0692	0.0781	0.0303
Capacity (GB)	4.7	15	27	23.8	61.7
Depth of focus (micron meter)	$2.15*\lambda$ 1.40	$2.15*\lambda$ 0.871	$1.102*\lambda$ 0.4463	$3.8*\lambda$ 2.47	$3.8*\lambda$ 1.54

The capacities shown in Table 1 are calculated according to the area density relative to conventional blue laser disk systems. The capacity of a disk is proportional to $1/(\text{spot area})$. The spot size and depth of focuses are calculated through vector diffraction theory. From Table 1 it can be seen that the Super-Red, which uses red light, can achieve a capacity comparable with that of conventional blue laser disk systems, while the Super-Blue can achieve about 60 GB capacity. If an 8-level recording method is used in the example embodiment, the capacity of the disk will be further increased three-fold, thus 71.4 GB for Super-Red and 185.1GB for Super-Blue disk. The maximum side lobe intensity is about 16%, as is shown in Fig. 7, and the axial intensity is invariant within the two wavelengths (z / λ).

Fig. 2 shows a modified embodiment from the embodiment of Fig. 1, where the pure phase type apodizer (116, Fig. 1) is replaced with a center obstructed phase and amplitude apodizer 202 after the radial polarization modulator 203. The use of this type

of apodizer 202 can reduce the second side lobe intensity to below 10%. The obtainable focused spot size and depth of focus are comparable with that of the embodiment of Fig. 1. In Fig.2, the prism beam shaper (105, Fig.1) is "merged" with the beam splitter (110, Fig. 1). The triangular shape part 204 of the "beam splitter and beam shaper" 206 acts as the beam shaper. The center 208 of the apodizer 202 is dark, which obstructs the center of the radial polarized beam 210, thus turning the beam 210 into a radial polarized annular beam 212 after passing through the apodizer 202. The apodizer 202 also provides a π phase difference modulation between the outer two belts 214, 216, which can reduce the focused spot size and make the focused beam uniform along the optical axis through interference near the focal plane 218.

Fig. 3 shows a modified embodiment from the embodiment of Fig. 2, where the apodizer (202, Fig. 2) is replaced with an annular beam shaper 302, and the radial polarization modulator 303 is positioned after the annular beam shaper 302. The annular beam shaper 302 shifts the lower spatial frequency light to a higher spatial frequency belt. After modulation by the polarization modulator 303, the light is focused by a focusing lens 306. With this setup, one can also obtain a focused spot size comparable with that obtained with the setup described in Fig. 1. The uniformity of the intensity along the optical axis and the super-resolution effect were found to be lower than that generated by the setup described in Fig.1, which is believed to be due to there being no phase modulation in this embodiment.

Fig. 4 shows a modified embodiment from the embodiment of Fig. 1, where the cylindrical lens (126, Fig. 1) is removed and the photo detector (128, Fig. 1) is replaced with a charge coupled device (CCD) 402. This setup can e.g. be used to perform optical coherent tomography or three dimensional optical imaging. In Fig.4, the beam shaper (105, Fig. 1) is "merged" with the beam splitter (110, Fig. 1). The triangular part 404 of the "beam splitter and beam shaper" 406 acts as a beam shaper. The apodizer 408 has more than two belts 411-415, with π phase difference between neighboring belts. Light from the radial polarization modulator 410 passing through the different belts 411-415 of the apodizer 408 interfere near the focal region 418, which reduces the spot size and makes the beam uniform along the optical axis. Also, since this setup can obtain high resolution and long depth of focus, if the detection optical path is removed in another embodiment, such a setup can serve as a high resolution optical lithography system.

Fig. 5 shows the intensity image 500 and illustrating the longitudinal field component phase contour plot in the X-Z cross-section of the focused beam from the

setup of the embodiment of Fig. 1. The field distribution is radially symmetric. The full width half maximum is 0.43λ and the depth of focus measured at 80% intensity is 3.8λ . The beam size is invariant along the optical axis within two wavelengths (z / λ).

Fig. 6 shows the axial intensity distribution of the focused beam of Fig. 5. The intensity is uniform within two wavelengths range near the focal plane.

Fig. 7 shows the radial intensity distribution. The maximum side lobe intensity is about 16%.

Fig. 8 shows an alternative annular beam shaper 800, which consists of two axicons 802, 804 merged together and disposed along the optical axis 806 of the optical focusing system (not shown). This annular beam shaper 800 can be used to replace the beam shapers 108, 302 in Fig. 1 and Fig. 3, in different embodiments.

The beam shapers 108, 302 and 800, the polarization modulators 112, 203, 303, and 410, and the apodizers 116, 202, and 408 are radial symmetric optical elements in the described example designs.

The described example embodiments utilize radial polarized light, to advantageously reduce the cross polarization effect for a high numerical aperture focusing system. Thus, the high super-resolution effect can be achieved in the described example embodiments. The beams generated by the example embodiments are also advantageously uniform along the optical axis, which minimizes the defocus spherical aberration.

Fig. 9 shows a flow chart 900 illustrating a method of optical focusing according to an example embodiment. At step 902, an incoming laser beam is shaped into a radial symmetric beam. At step 904, the radial symmetric beam is polarized into a radial polarized beam. At step 906, the radial polarized beam is focused at a focal plane.

The described embodiments have a number of applications, including in optical disk systems, scanning systems, confocal imaging systems, three dimensional imaging systems, lithography, alignment, optical tweezers, particle acceleration etc.

In one application, the described embodiments can provide a reading and writing optical pickup for the fourth generation optical data storage.

The described embodiments can achieve uniform spot size and uniform intensity distribution along the optical axis with extended depth of field, thus the defocus and spherical aberrations are advantageously eliminated, and the tolerance of disk substrate or cover layer thickness variation is improved. This can also allow having better control

over the reading/writing laser power and the writing mark length. The data transfer rate can also be increased by increasing the rotation speed.

In another application, embodiments can provide a stable scanning imaging system, where a certain defocus would have no or little effect on the scanning quality of the image.

In another application, embodiments can provide a three dimensional long depth of field super resolution imaging setup, in which the sample is almost uniformly illuminated along the optical axis and the longitudinal field component is dominant.

In another application, embodiments can provide a lithography system, where the intensity does not change along the depth of exposure.

It will be appreciated by a person skilled in the art that numerous variations and/or modifications may be made to the present invention as shown in the specific embodiments without departing from the spirit or scope of the invention as broadly described. The present embodiments are, therefore, to be considered in all respects to be illustrative and not restrictive.

CLAIMS

1. An optical focusing system comprising:
an optical beam shaper for shaping an incoming laser beam into a radial
5 symmetric beam;
a polarization modulator disposed such that the radial symmetric beam is a
radial polarized beam; and
a lens element for focusing the radial polarized beam at a focal plane.
- 10 2. The system as claimed in claim 1, further comprising an apodizer
element for introducing a Pi phase difference between different belts of the radial
polarized beam such that light from the different belts interferes at the focal plane.
- 15 3. The system as claimed in claims 1 or 2, further comprising an optical
element for forming an annular beam from the radial symmetric beam.
- 20 4. The system as claimed in claim 3, wherein the polarization modulator
is disposed before the optical element or after the optical element along an optical
path of the system.
- 25 5. The system as claimed in claims 3 or 4, wherein the optical element is
formed integral with the apodizer element.
6. The system as claimed in any one of the preceding claims, further
25 comprising a beam splitter for splitting a reading beam from the radial polarized
beam in reflection from the focal plane.
7. The system as claimed in claim 6, further comprising a lens unit for
focusing the reading beam.
- 30 8. The system as claimed in claim 7, further comprising a photo detector
for detecting the focused reading beam.

9. The system as claimed in claim 7, further comprising a CCD unit for performing imaging from the focused reading beam.

5 10. The system as claimed in any one of claims 6 to 9, wherein the beam splitter is formed integral with the beam shaper.

10 11. The system as claimed in any one of the preceding claims, wherein the system is configured in one of a group consisting of an optical disk system, a scanning system, a confocal imaging system, a three dimensional imaging system, a lithography system, an alignment system, an optical tweezer, and a particle acceleration system.

15 12. A method of optical focusing, the method comprising the steps of:
shaping an incoming laser beam into a radial symmetric beam;
polarizing the radial symmetric beam into a radial polarized beam; and
focusing the radial polarized beam at a focal plane.