INCREASING THE STORAGE DENSITY OF OPTICAL DISKS

Technical Field

This invention relates generally to the enhancement of the storage density of optical data storage media such as optical disks by the use of superresolution optics.

Background Art

There are a number of known ways to increase the storage density of existing optical disk systems. Among them, a most effective and straightforward approach is to use a shorter wavelength laser diode. Although great advances have been made in developing blue-green laser diodes in the past few years, it seems that there is still some time to go before such diodes become commercially available. Other efforts have been directed to increasing recording density through the use of various superresolution techniques which can provide a moderate optical response even beyond the cut-off frequency of the optical disk system.

The most widely investigated superresolution technique is to modify the laser spot profile at the recording plane. This can be achieved either through modifying the disk structure, eg. a groove and land recording [N. Miyagawa, Y. Gotoh, E. Ohno, K. Nishiuchi and N. Akahira, Appl. Phys. Lett. **59**, 1272 (1991)], or through using the characteristics of laser induced temperature rise in the recording layer, eg. magnetically induced superresolution (MSR) [M. Kaneko, K. Aratani, A. Fukumoto and S. Miyaoka, Proceedings of the IEEE, **82**, 544 1994]. In the former case, information pits are stored on both the lands and the grooves. During signal readout, the land and groove structure provides an additional phase delay to the light reflected back from a groove with respect to the light reflected from the two adjacent land areas. It has been shown both theoretically and experimentally that the cross talk between adjacent tracks can be reduced to an acceptable level through modifying the groove width and depth [N. Miyagawa, Y. Gotoh,

E. Ohno, K. Nishiuchi and A. Akahira, *Technical Digest Symposium on Optical Memory* (1994) P.35]. This technique, however, increases the recording density only in the radial direction.

On the other hand, in the MSR technique, a non-uniform temperature distribution induced by laser beam is effectively used to mask out a certain portion of the laser spot at the recording plane, which is equivalent to a size reduction of the laser spot. This becomes possible because the highest temperature region induced by the laser beam is generally ahead of the peak intensity position of the laser spot in the disk rotation direction. It is also for this reason, that the performance of the MSR technique exhibits a strong dependence on the disk structure and rotation speed. Although this technique was originally discussed in connection with magnetooptic disks, it has been extended to other types of optical disks including a possible approach to solving the disk structure and rotation speed sensitivity problem [Y. Wu and B.M.N. Yussof, Appl. Phys. Lett. **66**,911 (1995)].

Another superresolution technique is to modify the laser beam at the entrance aperture of the objective lens [H. Ando, T. Yokota and K. Tanoue, Jpn. J. Appl. Phys. **32**, 5269 (1993)]. This technique, however, can only increase the high-frequency response with respect to that in the low-frequency region : it still cannot break the physical limit of the optical system. Therefore, the improvement in storage density is quite limited.

Disclosure of the Invention

In view of the above, it is an object of the present intention to provide a superresolution technique, and an optical configuration therefor, that is capable of increasing the recording density both in the radial and track directions but also is independent of the disk structure.

The invention accordingly provides, in one aspect, an optical configuration for optically reading data on a data storage medium, eg. an optical disk, including lens means to focus an incident light beam onto the medium, characterised in that said lens means is arranged to also focus the incident light beam to an intermediate position, and in that there is provided at such intermediate position spatial filter means having a filter function to enhance resolution of the read-out optics for reading the information pits recorded on the data storage medium.

In another aspect, the invention provides a method of reading data on a data storage medium, eg. an optical disk, whereby the data recording density on the medium may be increased, characterised by:

modifying the lens system of the optical configuration to focus the incident light beam to an intermediate position, and providing at said intermediate position spatial filter means having a filter function to enhance resolution of the read-out optics for reading the information pits recorded on the data storage medium.

Brief Description of the Drawings

The invention will be further described, by way of example only, with reference to the accompanying drawings, in which:

Figure 1 depicts schematically an optical configuration according to an embodiment of the invention, for an optical disk reading system;

Figures 2(a) to (c) are diagrams which illustrate calculated amplitude modulation transfer functions (MTF) for the configuration shown in Figure 1, for various values of filter width a and phase step ϕ;

Figure 3 indicates the calculated areas under each of the MTF curves of Figures 2(a) to (c); and

Figure 4 illustrates a modified condenser lens for the embodiment of Figure 1.

Mode(s) for carrying out the Invention

The optical disk system 10 shown schematically in Figure 1 differs from a conventional optical disk system in the addition of a condenser lens 2 and a spatial filter 3. The condenser lens 2 is employed to focus the scanning laser beam 8 into a spot 9 with an appropriate size and projects the beam onto the spatial filter 3. The modulated laser beam emerging from the spatial filter is directed to the objective lens 5 which focuses the modulated laser beam into a tiny spot on the information layer or data storage surface 7 of the optical disk 6. It will be seen from Figure 1 that the spatial filter and the initial focus are in the image conjugate plane of information layer 7. The reflected light is reflected at a half-mirror 4 onto a detector 12.

The basic principle of achieving superresolution by this configuration can be understood through evaluating its modulation transfer function, as follows.

The amplitude distribution of the light at the focal plane of the objective lens 5 can be written as

$$A_d(x_d, y_d) = -\frac{exp\{-jkd_1(1+M)\}}{\lambda^2 M d_1^2} exp\frac{-jk}{2Md}(1+\frac{1}{M})(x_d^2+y_d^2) \times \iint_{-\infty}^{\infty} t(x_o, y_o)h(x_o + x_d/M, y_o + y_d/M)dx_o dy_o, \quad (1)$$

where M is the magnification of the objective lens, $t(x_O,y_O)$ is the filter function, d_1 and d_2 (Figure 1) are the object and image distances from lens 5, respectively, and h is the point spread function which is given by the Fourier transform of the pupil function of the objective lens $P(u,v)$. The effective pupil function $P_E(u,v)$, in turn, can be obtained by performing reverse Fourier transform on $A_d(x_d,y_d)$. Once $P_E(u,v)$ is known, the optical transfer function (OTF) of the system can be derived from the autocorrelation of the effective pupil function. The square root of OTF gives the amplitude modulation transfer

function (MTF) which will be used in the following context to discuss the performance of the optical disk system.

Although Eq.(1) can be solved numerically, here we just consider an ideal case in which the meaning of Eq.(1) will become much clearer. Assume that the diameter of the objective lens is infinitely large, ie. *h* is a delta function; then Eq.(1) reduces to:

$$A_d(x_d, y_d) = -\frac{exp\{-jkd_1(1+M)\}}{\lambda^2 M d_1^2} exp\frac{-jk}{2Md_1}(1+\frac{1}{M})(x_d^2+y_d^2)t(x_d/M, y_d/M). \quad (2)$$

Considering the fact that $x_d(y_d)$ is comparable to λ but much smaller than d_1, Eq.(2) can be further simplified to be $A_d(x_d,y_d) = t(x_d/M,y_d/M)exp(-j\psi)$ with ψ as a constant phase factor. This means that, in the ideal case, the amplitude distribution is just a reduced replica of that of the spatial filter. Of course, in practical cases one can only obtain a blurred replica due to the limited bandwidth of the optical system. For simplicity, in what follows this special case is considered.

For purposes of further exemplification and explanation, we assume that the amplitude distribution of light at the spatial filter plane is the Fourier transform of a truncated Gaussian beam and further assume that the laser intensity at the edge of the entrance pupil of the condenser lens 2 is 25% of the peak intensity of the laser beam. Under these conditions, we obtain a laser spot with a full width at half maximum (FWHM) of about 4.5μm. Simulations have been done for a square phase-shift filter described by

$$t(x_o, y_o) = \begin{cases} 1 & : \ |x| \le a \ \ \& \ \ |y| \le a \\ exp(j\phi) & : \ \text{others}, \end{cases} \quad (3)$$

where *a* and ø are adjustable constants for tuning the filter dimension and magnitude of phase shift.

Figs.2a-2c show the calculated MTF's with different filter width a and phase step ø. Calculations have been carried out for filters with a width of 2, 3 and 4μm, and with the phase shift changing from 0 to 120° at a step of 20°. ø = 0 corresponds to the case that there is no filtering effect, in which the maximum spatial frequency is given by 2NA/λ. With the use of a filter, however, the optical system shows a moderate response even beyond the cut-off frequency. It is also clear from the figures that the degree of improvement is strongly dependent on the magnitude of the phase shift. The high frequency MTF initially increases rapidly with increasing ø up to 80° and then saturates or even begins to decrease at 100°-120°. It should be noted that the improvement at high-frequency is obtained at the price of reduced optical sensitivity at lower frequency. If the low-frequency response decreases to a certain level, the over-all system performance will be degraded. In other words, there should exist an optimised filter structure for a specific optical disk system.

Although it is difficult to judge which filter is most desirable for practical applications based only on the MTF curves, some useful rough estimation is possible through looking at the areas under each curve. The larger the areas the higher the average resolution if we assume that the information pits are quite uniformly distributed in the spatial frequency domain. Figure 3 shows the calculated areas under each of the MTF curves shown in Figs.2a-2c which are plotted as a function of ø for three different filter widths. It is interesting to note that all the curves exhibit a maximum in the range of 40°-60° which is almost in the same range in which minimised crosstalk has been obtained for land and groove recording [N. Miyagawa, Y. Gotoh, E. Ohno, K. Nishiuchi and N. Akahira, Appl. Phys. Lett. **59**, 1272 (1991), cited above]. This is perhaps not unexpected because the technique used in this invention has a similar effect as that of the land and groove approach; the significant difference is that the present approach can improve the resolution both in the tangential and radial directions while the land and groove recording increases the density in the radial direction only.

Accordingly, the spatial filter is provided with a filter function $t(x_o,y_o)$ selected, if necessary empirically, to enhance resolution of read-out optics for reading the information pits on the data storage surface.

In the above implementation, we have assumed that the spatial filter 3 has a fixed function. Instead, it can also or alternatively be an electrically controllable filter which can be used to optimise the transfer function from a control unit 32, during the readout process for each specific disk. The control unit 32 can either be a separate circuit or a part of the functionality from the micro-controller of the optical disk system.

Condenser lens 2 can be a conventional index-type lens. Alternatively, for example to reduce the cost of implementation, the laser source can be a surface emitting laser diode 15 and the condenser lens a diffraction grating lens 16 formed together with the laser diode 15, as depicted in Figure 4.

It will also be understood that the term "comprises" or its grammatical variants as used herein is equivalent to the term "includes" and is not to be taken as excluding the presence of other elements or features.

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CLAIMS

1. An optical configuration for optically reading data on a data storage medium, eg. an optical disk, including lens means to focus an incident light beam onto the medium, **characterised in that** said lens means is arranged to also focus the incident light beam to an intermediate position, and in that there is provided at such intermediate position spatial filter means having a filter function to enhance resolution of the read-out optics for reading the information pits recorded on the data storage medium.

2. An optical configuration according to claim 1, further characterised in that said filter means has a predetermined filter function.

3. An optical configuration according to claim 1, further characterised in that said filter means has an adjustable filter function.

4. An optical configuration according to claim 3, further characterised by means to selectively adjust said filter function.

5. An optical configuration according to any preceding claim, further characterised in that said lens means includes a condenser lens on a surface emitting laser which emits light to form said scanning beam.

6. An optical configuration according to claim 5, further characterised in that said condenser lens is a diffraction grating lens.

7. An optical configuration according to any one of claims 1 to 4, wherein said lens means includes an objective lens and a condenser lens, and said intermediate position is at the image conjugate plane of the data storage medium, relative to the objective lens.

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8. A method of reading data on a data storage medium, eg. an optical disk, whereby the data recording density on the medium may be increased, **characterised by**:

modifying the lens system of the optical configuration to focus the incident light beam to an intermediate position, and providing at said intermediate position spatial filter means having a filter function to enhance resolution of the read-out optics for reading information pits recorded on the data storage medium.

9. A method according to claim 8, further characterised in that the lens system is modified by adding a condenser lens, and by providing for the intermediate position to be at the image conjugate plane of the data storage medium, relative to an objective lens.

10. A method according to claim 8 or 9, further characterised in that said filter means has a predetermined filter function.

11. A method according to claim 8 or 9, further including adjusting the filter function of the spatial filter means.

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