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TECHNICAL PAPER

Angle compensation of the reference beam in a retrieving process of the holographic data storage system

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Abstract Holographic data storage system is one of a strong candidate of the next generation high capacity data storage system with a high storage density and a fast data transfer rate. The holographic data storage system uses two beams in a recording process and only a reference beam is used for retrieving stored data. With the angle multiplexing when the angle of the reference beam is deviated from its correct point, the diffraction efficiency of the corresponding data page is reduced and SNR is decreased. Therefore it is necessary to compensate the angle of the reference beam to reconstruct a good data page. To compensate the angle error, the angle of the reference beam is changed precisely within a specific range and stopped at the angle with the highest diffraction efficiency. By this method, in a retrieving process if there is a difference between the real angle of the reference beam and its correct angle, the error can be compensated and the best data page can be obtained.

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1 Introduction

Today many removable data storage media are shaped as a disk. Especially almost all optical data storage systems has a disk type medium and the holographic data storage system (HDSS), one of the next generation optical memory system, also uses a disk type photopolymer medium (Coufal et al. 2000). At first a cubic type photorefractive crystal and a disk type photopolymer were in competition, but nowadays because of some characteristics the photopolymer is selected as a medium of HDSS.

During writing or retrieving process, the disk type medium is rotating and a vibration of the disk must be induced. A vibration of the disk is one of main disturbance sources, and it is called as the ‘disk tilt’. There have been many efforts to reject the disturbance from the tilt in conventional optical disk drive (ODD) systems and the HDSS must have the same problem caused by the disk tilt.

In conventional ODD the disturbance by the disk tilt appears as a focusing error signal and many types of controllers are studied to remove the disturbance. The controllers of conventional ODD can be constructed because the focusing and tracking error signals are able to be observed from the system but in case of the HDSS it is hard to get the error signal by the effect of the disk tilt. Therefore it is needed to get the quantity of an error by the tilt and an algorithm to correct the error for HDSS.

In this paper, a new concept for estimating the error from the disk tilt and retrieving the best image of the data page is proposed. The effect of the disk tilt is analyzed and the method to get the data page with the highest diffraction efficiency is studied.

2 Angle multiplexing method of HDSS

Comparison with conventional storage devices such as CD or DVD, one of the unique features of holographic data storages is multiple data recording capability at the same position in recording materials; which is called as multiplexing. Retrieval of an individual page with minimum crosstalk from the other pages is a consequence of the volume nature of the recording and its behavior as a highly tuned structure. This effect, known as the Bragg effect, shows how the efficiency of reconstruction from a hologram decreases as the reference angle or wavelength deviates from the recording condition.

The simplified holographic recording structure for angle multiplexing is given in Fig. 1 (Coufal et al. 2000). Due to the simple structure, angle multiplexing is generally used in holographic recording (Coufal et al. 2000; Li and Psaltis 1995; Rastani 1993; Kogelnik 1969; Li and Psaltis 1994; Mok 1993). Recently it is used widely with modification using polytopic filter and called as a new multiplexing method—polytopic multiplexing. But the basic principles are same with angle multiplexing. When angle multiplexing is performed, a plane wave reference beam is controlled by the reference beam steering mechanism. The minimum angle deviation to mismatch Bragg condition is called as “angle selectivity” and the angle selectivity is defined as follows (Coufal et al. 2000; Li and Psaltis 1994).

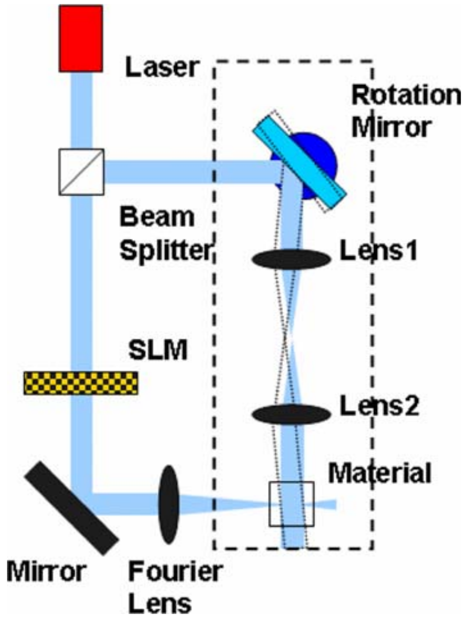


Fig. 1 Typical holographic recording structure for angle multiplexing

$$\Delta\theta = \frac{\lambda}{nd}\frac{\cos\theta_S}{\sin(\theta_R+\theta_S)}, \tag{1}$$

where λ is a wavelength of the laser, d is the thickness of the recording material, n is the index of refraction of recording material. θ_R and θ_S denote the incidence angles of a reference beam and a signal beam to the normal to the recording material surface. The diffraction efficiency is maximum when $\Delta\theta = 0$.

For accurate understanding of angle multiplexing, the brief review of the diffraction efficiency derived coupled wave theory is necessary. For the lossless dielectric grating of the transmission type hologram, the diffraction efficiency η for angle multiplexing is derived from the coupled wave theory as follows (Kogelnik 1969)

$$\eta = \frac{\nu^2\sin^2\sqrt{(\nu^2+\xi^2)}}{(\nu^2+\xi^2)}, \tag{2}$$

where ν and ξ are defined respectively in Eq. 3.

$$\nu = \frac{Kd}{\cos\theta_R}, \quad \xi = \Delta\theta\frac{2\pi}{\lambda}nd\sin\theta_R, \tag{3}$$

K is the coupling constant, which is $K = \pi\,\Delta n/\lambda$ for TE wave, the electric field perpendicular to the plane of incidence, and $K = (-\pi\,\Delta n\cos 2\theta_R)/\lambda$ for a TM wave. Variations of the index modulation Δn are ignored here. The angular selectivity of a hologram is determined from Eq. 2. η goes to zero for $(\nu^2+\xi^2) = \pi^2$. If we substitute Eq. 3 with assumption of TE incident wave, in a recording medium with $\Delta n \ll \lambda/d$, the angular selectivity can be described simply (Rastani 1993)

$$\Delta\theta = \frac{\lambda}{nd\sin\theta}. \tag{4}$$

Equation 4 is the special case $\theta_S = \theta_R = \theta$ of Eq. 1.

The relationship of Eqs. 2 and 3 is described in Fig. 2. In general $\nu = \pi/4$ curve is used and the point $\eta = 0$ near $\xi = 3$ is the first null point. In order to write and retrieve data without crosstalk, it is better to superimpose holograms at the latter null points after second.

Hence the angle multiplexing superimposes many holograms by changing the incident angle of the reference beam with a very small degree which is very sensitive to the disk tilt. Tilt margin of the holographic data storage system with a disk type medium is calculated with the below equation.

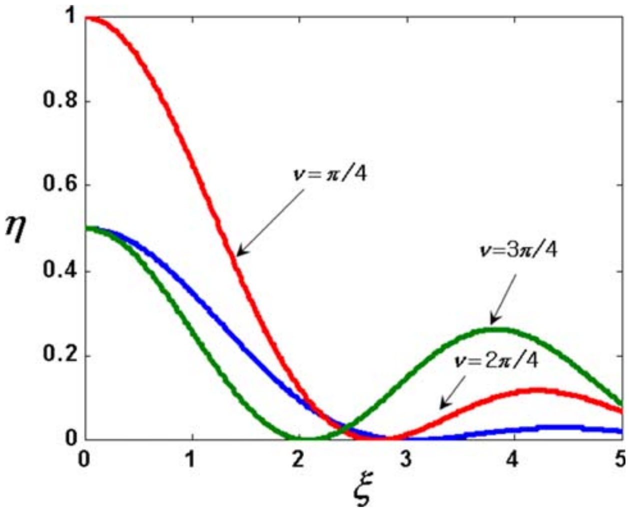


Fig. 2 Diffraction efficiency for angle multiplexing

$$T_{\mathrm{m}} = \frac{\lambda}{d(\mathrm{NA})^3}, \qquad (5)$$

where T_{m} is the tilt margin of the system and NA is the numerical aperture.

Generally tilt margin of HDSS using angle multiplexing is less than 0.1° with parameter values like next: d is about 1 mm, λ is 532 nm and NA is 0.3.

3 Effect of disk tilt

In case of the angle multiplexing, the disk tilt causes unwanted disturbance. The angle multiplexing method can be divided into two types according to the direction of the reference beam. If the signal beam is illuminating from the front side of the medium (disk), the direction of the reference beam can be located in the tangential direction or in the radial direction about the disk. The effects of the disk tilt with respect to the direction of the reference beam are shown in Fig. 3. The disk tilt acts as a fractal-direction disturbance in case of Fig. 3a and acts as an angle-direction disturbance in case of Fig. 3b. When the disk tilt affects as an angle-direction disturbance, the system is so sensitive to the BER that it is necessary to compensate the angle of the reference beam in order to get the best retrieved image.

Without any disturbance, the reference beam enters to the disk at the same angle with that used in writing process. That is $\theta_{\mathrm{in}} = \theta_{\mathrm{R}}$. Where θ_{in} is the incident angle of the reference beam in retrieving process and θ_{R} is the angle of the reference beam used in writing process. However because of the angle-direction disturbance, the disk tilts with the angle ± θ_{tilt} and the incident angle is changed. With respect to the change of angle of the reference beam, the diffraction efficiency of the data page is decreased. Change of the incident angle of the reference beam and decrement of diffraction efficiency corresponding to the tilt angle are depicted in Fig. 4. Figure 4a is the ideal case without disturbance. The incident angle of the reference beam is increased by tilt angle $+\theta_{\mathrm{tilt}}$ in Fig. 4b and the diffraction efficiency is decreased by the reason that the data page is retrieved at the marked point in Fig. 4d. Figure 4c and e depict the case of tilt angle $-\theta_{\mathrm{tilt}}$.

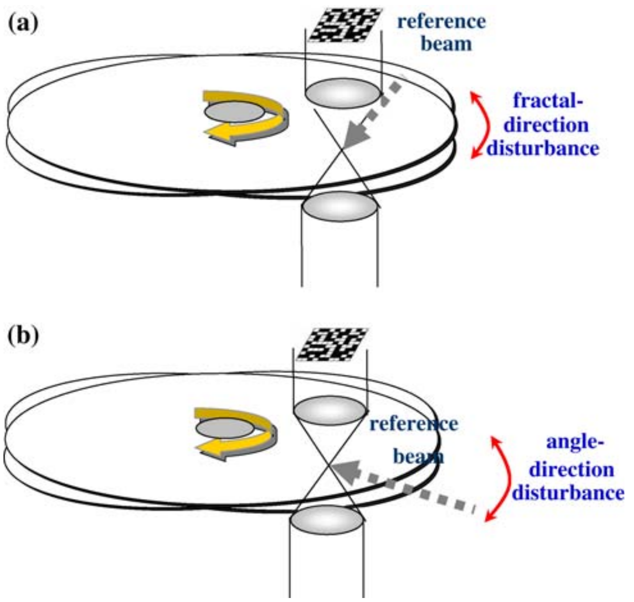


Fig. 3 Effect of the disk tilt **a** as a fractal-direction disturbance **b** as an angle-direction disturbance

Figure 5 is the retrieved images of data page captured by CCD camera. Figure 5a is captured without disturbance and Fig. 5b is captured with disturbance. As shown in the figure diffraction efficiency of Fig. 5b is decreased.

The diffraction efficiency of the retrieved data page has the maximum value when the angle of the reference beam in retrieving process is equal to the corresponding angle used in writing process. As the angle of the reference beam is changed from the correct point, the diffraction efficiency decreases. The disturbance in the angle-direction can change the incident angle of the reference beam and the diffraction efficiency can be decreased by the amplitude of the disturbance.

The change of the diffraction efficiency with respect to the angle of the reference beam is shown in Fig. 6. The black dashed line represents theoretical diffraction efficiency and the blue line is the real value from experiments.

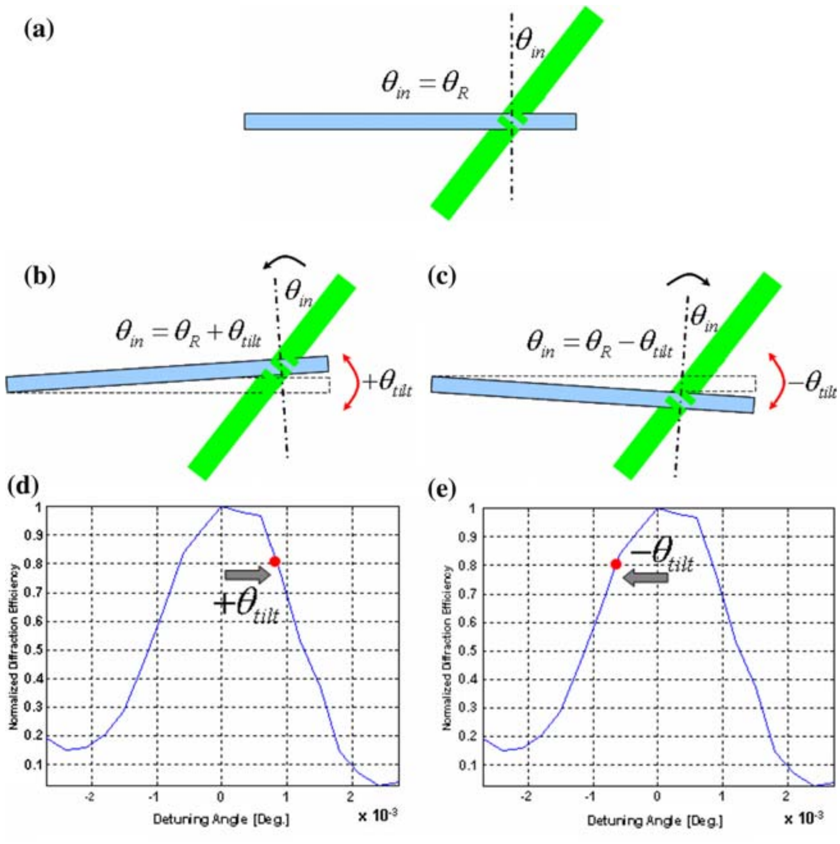


Fig. 4 Change of angle of reference beam and decreasing diffraction efficiency by disk tilt. **a** Without disturbance **b** change of incident angle with tilt angle $+\theta_{tilt}$ **c** change of incident angle with tilt angle $-\theta_{tilt}$ **d** diffraction efficiency at incident angle $\theta_R + \theta_{tilt}$. **e** diffraction efficiency at incident angle $\theta_R - \theta_{tilt}$

The real value curve does not have 0 diffraction efficiency at the null points(±0.0024°). That is because a diffused light enters to the camera or a residual data written at the point of the medium. The two curves have similar shape thus the theoretical value curve will be used for the simulation.

4 Compensation algorithm

Because the angle of the reference beam can be changed by the disturbance, it would occur that the distorted data page is retrieved with a wrong angle of the reference beam. Therefore it is necessary to search the angle for the best retrieved image. It is certain that the best image will be received at the angle with the maximum diffraction efficiency.

With existence of the angle-direction disturbance, to find the exact angle of the reference beam for the best retrieved image, the angle with the maximum diffraction efficiency is found with the back propagation algorithm of the neural network. The input of the back propagation algorithm is the diffraction efficiency of the retrieved image and the algorithm finds the maximum value of the input by changing the angle of the reference beam.

Back propagation is a famous algorithm for finding an optimal value. By using this algorithm, the exact angle can be found without a danger of falling into a local extreme value.

The incident angle of the reference beam is compensated to the exact angle with rotating the galvano mirror.

4.1 Neural network

A neural network is a massively parallel distributed processor that has a natural propensity for storing experiential knowledge and making it available for use (Haykin 1998). It resembles the brain in two respects:

Knowledge is acquired by the network through a learning process.

Interneuron connection strengths known as synaptic weights are used to store the knowledge.

The procedure used to perform the learning process is called a learning algorithm, the function of which is to modify the synaptic weights of the network in an orderly fashion so as to attain a desired design objective.

The modification of synaptic weights provides the traditional method for the design of neural networks.

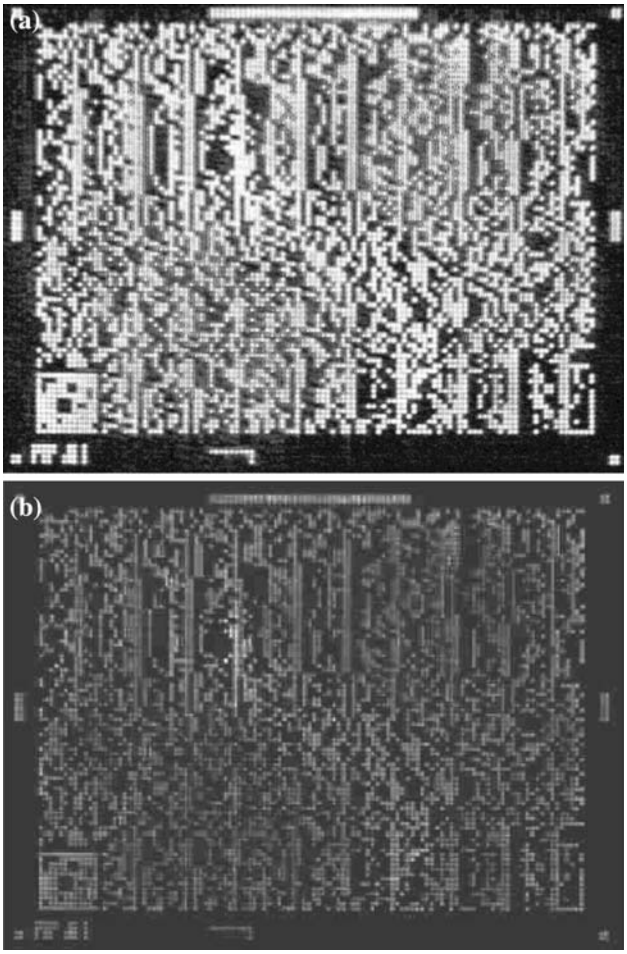


Fig. 5 Captured image by CCD. **a** Without disturbance **b** with disturbance

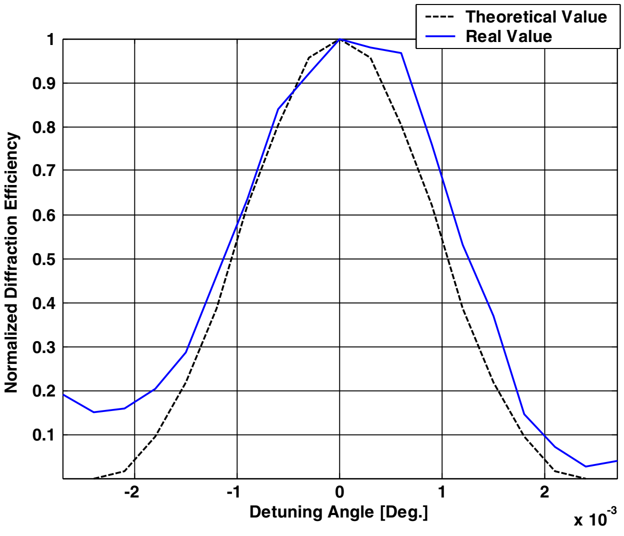


Fig. 6 Normalized diffraction efficiency with respect to the angle of the reference beam

Such an approach is the closest to linear adaptive filter theory, which is already well established and successfully applied in such diverse fields as communications, control, radar, sonar, seismology, and biomedical engineering. However, it is also possible for a neural network to modify its own topology, which is motivated by the fact that neurons in the human brain can die and that new synaptic connections can grow.

4.2 Back propagation algorithm

The back propagation algorithm makes the network to learn until the output vector being resembled with the input vector or classified into proper input vector. To minimize mean square error of the network control weights and biases using back propagation rules. This procedure changes weights and biases for the direction of reducing the error as fast as possible. The variations of weights and biases are proportional to the effects of the elements about mean square error of the network.

It often happens to get not the global minimum but the local minimum when using back propagation learning. For that case to get the global minimum it is necessary to construct the network with more neurons and layers, then the problem becomes complex. Sometimes using another initial condition can solve the problem.

The algorithm cycles through the training data $\{[x(n), d(n)];\ n = 1, 2, \ldots, N\}$ as follows.

1. Initialization

   Start with a reasonable network configuration, and set all the weights and threshold levels of the network to small random numbers that are uniformly distributed.

2. Presentations of training examples

   Present the network with an epoch of training examples. For each example in the set ordered in some fashion, perform the following sequence of forward and backward computations under points 3 and 4, respectively.

3. Forward computation

   Let a training example in the epoch be denoted by $[x(n), d(n)]$, with the input vector $x(n)$ applied to the input layer of sensory nodes and the desired response vector $d(n)$ presented to the output layer of computation nodes. Compute the activation potentials and function signals of the network by proceeding forward through the network, layer by layer. The net internal activity level $v_j^{(l)}(n)$ for neuron j in layer l is

$$v_j^{(l)}(n) = \sum_{i=0}^{p} w_{ji}^{(l)}(n)\, y_i^{(l-1)}(n), \tag{6}$$

where $y_i^{(l\text{-}1)}(n)$ is the function signal of neuron i in the previous layer l–1 at iteration n and $w_{ji}^{(l)}(n)$ is the weight of neuron j in layer l that is fed from neuron i in layer l–1. For $i = 0$, we have $y_0^{(l\text{-}1)}(n) = -1$ and $w_{j0}^{(l)}(n) = \theta_j^{(l)}(n)$, where $\theta_j^{(l)}(n)$ is the threshold applied to neuron j in layer l. Assuming the use of a logistic function for the sigmoidal nonlinearity, the function (output) signal of neuron j in layer l is

$$y_j^{(l)}(n) = \frac{1}{1 + \exp\left(-v_j^{(l)}(n)\right)}. \tag{7}$$

If neuron j is in the first hidden layer (i.e., $l = 1$), set

$$y_j^{(0)}(n) = x_j(n), \tag{8}$$

where $x_j\,(n)$ is the jth element of the input vector $x(n)$. If neuron j is in the output layer (i.e., $l = L$), set

$$y_j^{(L)}(n) = o_j(n). \tag{9}$$

Hence, compute the error signal

$$e_j(n) = d_j(n) - o_j(n), \tag{10}$$

where $d_j\,(n)$ is the jth element of the desired response vector $d(n)$.

4. Backward computation

   Compute the δ's (i.e., the local gradients) of the network by proceeding backward, layer by layer:

$$\delta_j^{(L)} = e_j^{(L)}(n)\, o_j(n)\left[1 - o_j(n)\right]$$

for neuron j in output layer L

$$\delta_j^{(l)}(n) = y_i^{(l)}(n)\left[1 - y_j^{(l)}(n)\right]\sum_k \delta_k^{(l+1)}(n)\, w_{kj}^{(l+1)}(n) \tag{11}$$

for neuron j in hidden layer l.

   Hence, adjust the weights of the network in layer l according to the generalized delta rule:

$$\begin{aligned} w_{ji}^{(l)}(n+1) &= w_{ji}^{(l)}(n) + \alpha\left[w_{ji}^{(l)}(n) - w_{ji}^{(l)}(n-1)\right] \\ &\quad + \eta\,\delta_j^{(l)}(n)\, y_i^{(l-1)}(n), \end{aligned} \tag{12}$$

where η is the learning-rate parameter and α is the momentum constant.

5. Iteration

   Iterate the computation by presenting new epochs of training examples to the network until the free parameters of the network stabilize their values and the average squared error computed over the entire training set is at a minimum or acceptably small value. The momentum and the learning-rate parameter are typically adjusted (and usually decreased) as the number of training iterations increases.

5 Results

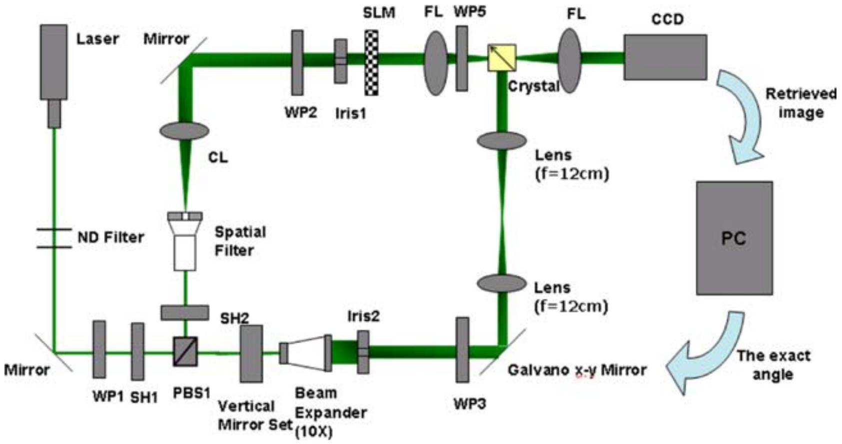
5.1 Simulation results

The structure of the system is in Fig. 7. When the retrieved image is taken by a CCD camera, the image is imputed to a computer and the diffraction efficiency of the image is calculated. Then the galvano mirror changes the angle of the reference beam to the exact position with the largest value of the diffraction efficiency by the compensation algorithm.

If there is an angle-direction disturbance in the retrieving process, the angle of the galvano mirror would be deviated from its exact position. Let the angle of the exact position is 0°. Then by the disturbance, the angle of the reference beam is set to the random angle from –0.0024 to 0.0024° (As shown in Fig. 6 the angle selectivity of the system is 0.0024°). If the angle is not 0°, the diffraction efficiency of the retrieved image must not have the maximum diffraction efficiency. When the retrieved image is captured by CCD camera, the image goes to a computer. The computer calculates a diffraction efficiency of the image and rotates the galvano mirror by a small amount (e.g. the smallest angle with a resolution of itself –0.0003° galvano mirror is used in our system). At the angle of a smallest rotating of galvano mirror, the same image will be captured with a different value of diffraction efficiency. The value of diffraction efficiency can be decreased or increased. The value of the diffraction efficiency is imputed to the back propagation algorithm and the algorithm begins to find the maximum value of the diffraction efficiency by rotating the galvano mirror. The compensation algorithm will search the angle with the maximum diffraction efficiency, exactly maybe 0°.

Figure 8 is the results of the simulation. The variation of the angle and the calculated diffraction efficiency is shown in Fig. 8a and the start and final angle is shown in Fig. 8b. The algorithm can search the exact angle of the reference beam with several iterations. The number of iteration is called as an epoch and it is less than 10 times in almost all simulations.

Fig. 7 System structure



At the angle found by the algorithm the retrieved image will have the maximum diffraction efficiency.

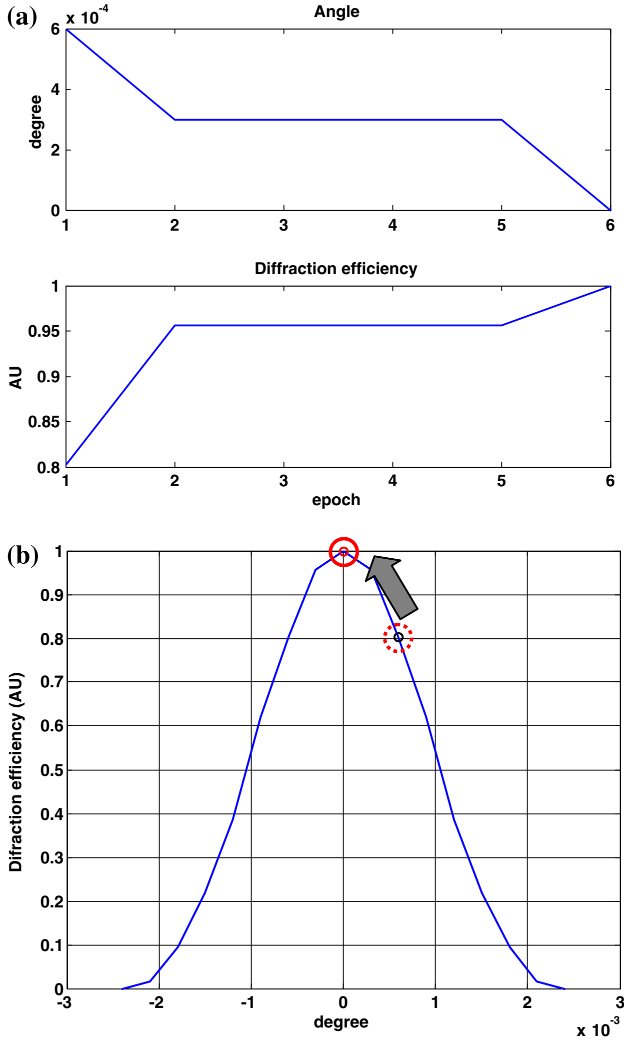


Fig. 8 Simulation results. **a** Process for finding the exact angle **b** change of the point for retrieving the data page

5.2 Experimental results

Figure 9 is the captured images by the camera. Diffraction efficiency is proportional to intensities of pixels of the image. Without the compensation algorithm the retrieved image has low diffraction efficiency like Fig. 9a. Summation of intensities of the pixels of Fig. 9a is 8930834 in 256 level gray-scale. With the compensation algorithm the data page of Fig. 9b can be obtained and summation of intensities is 17364371. Therefore diffraction efficiency becomes higher by 194%.

Although amount of the tilt angle can not be detected, the disk tilt can be compensated with the compensation algorithm.

6 Conclusions

With a disk type medium, the HDSS can not keep away from a disturbance by the disk tilt. When the reference beam is illuminated in the radial direction, the disk tilt affects to the system like an angle-direction disturbance. In this case, the retrieved image is distorted by the disturbance so that the diffraction efficiency of the data page is decreased seriously.

To retrieve the best image, it is necessary to compensate the angle of the reference beam deviated by the angle-direction disturbance. To compensate the angle of the reference beam, the angle with which the retrieved image has the maximum value of diffraction efficiency is found with the back propagation algorithm of the neural network. With the compensation algorithm data page with higher diffraction efficiency could be obtained. The diffraction efficiency increases by 210% comparing to the retrieved image without the compensation algorithm.

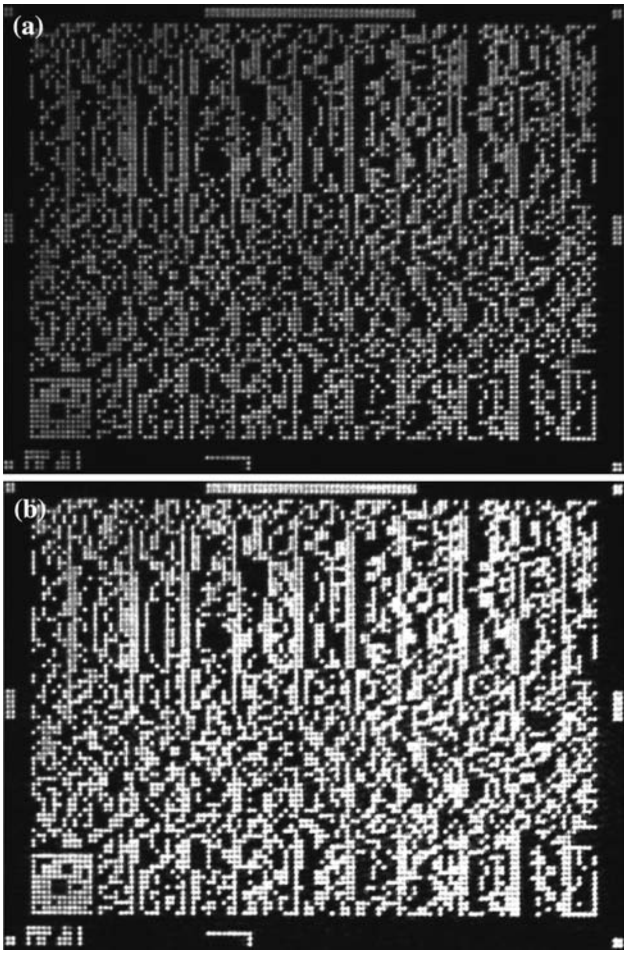


Fig. 9 Retrieved images existing the angle-direction disturbance. **a** Without the compensation algorithm **b** with the compensation algorithm

If the disk tilt act like an angle-direction disturbance, the best image can be retrieved with the angle of the reference beam compensated by the suggested algorithm.

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