The compensability between the longitudinal and transverse mismachining tolerance of grating in the optical pick-up head

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In this paper numeric analysis is made to the influence of the longitudinal mismachining tolerance (LMT) and the transverse mismachining tolerance (TMT) of the grating in the optical pick-up head (GOPH) of VCD, DVD, and CD-ROM on the transmissivity and the intensity ratio of the auxiliary light beam to the main read-write light beam (IRAM) by using the general expression of diffraction efficiency obtained from the scalar diffraction theory. On solving GOPH problem, the scalar diffraction theory and the vector diffraction theory are coincident, and the scalar diffraction theory is reliable. The result shows that LMT and TMT can compensate for the inverse effect of IRAM, however, at the expense of reducing transmissivity. As far as GOPH is concerned, the goodness that LMT and TMT can be effectively compensated for is very advantageous in manufacturing of the grating.

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At present, VCD, DVD, and computer are very popular all over the world, it is a very promising and profitable area that many people concern. Optical pick-up head is one of the core accessories in these electronic products. Rectangular grating in the optical pick-up head (GOPH) is used to detect, find, write, and read signal, and its properties determine the performance of read-write signal.

Liang *et al.*[1,2] introduced the principle of detecting, focusing and finding for disk signal in detail combined international front-situation[3,4], and also tried to make a sample grating[1]; Zhang *et al.*[5,6] analyzed deeply the errors of verticality of side wall and surface roughness for GOPH on the point of theory. These works are significant as of theory guidance to the manufacture of GOPH. In order to accelerate the industrial process of GOPH of VCD and DVD, a few scientists in CIOMP (Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences) have performed insight research of theory and experiment based on previous work for two years, they are preparing for the state industrialization of GOPH in urgency, and a few standard master gratings are productive. This paper reports a part of the work.

It is well known that properties[7−11] of diffracted field must be analyzed by the rigorous vector diffraction theory when period size of grating is in the order of sub-wavelength. While the period size of GOPH is two orders larger than its working wavelength, the value of Q[10,11] is far less than 1, therefore, the diffraction efficiency can be calculated enough accurately by the scalar theory. GOPH is a kind of rectangular phase grating whose duty cycle is 1/2 in order that the diffraction intensity of even orders is zero, because the pick-up head is a component that could read and write information by the light beam of zero order (the main light beam) and could test and trace error signal by the light beam of ±1 orders (the auxiliary light beams). In addition, the read-write function of GOPH is realized by the cooperation of diffracted wave of the zero order and ±1 orders. It does not demand the maximum value of diffraction efficiencies of the ±1 orders but needs manual matching in diffraction efficiency of the zero order and those of ±1 orders. It is necessary that groove depth of GOPH is designed on the base of the requirement of read-write system to the intensity ratio of the diffracted wave of ±1 orders to that of zero order. Moreover, if the duty cycle of the grating does not equal 1/2, stray light is induced to interfere read-write signal, and dismatch in diffraction efficiency of the zero order and those of ±1 order appear. Consequently, it is quite necessary to study the influence of the longitudinal mismachining tolerance (LMT) and the transverse mismachining tolerance (TMT) on the intensity ratio of the auxiliary light beam to the main read-write light beam (IRAM) for the design and manufacturing of GOPH.

The sectional drawing for rectangular grating is depicted in Fig. 1, where d is the grating period, τ is the groove width, $\rho = \tau/d$ is duty cycle, h is the groove depth, H is the thickness of foundation base, and n is the refractive index of grating material.

Here we define that rays 1 and 2 are incident upon the grating at an angle of incidence θ, ε is refractive angle. The phase lag produced by ray 1 through the grating can be expressed as

$$\phi_1 = \frac{2\pi}{\lambda}(H+h)\left(\frac{n}{\cos\varepsilon} - \frac{1}{\cos\theta}\right). \quad (1)$$

The phase lag produced by ray 2 through the grating can be expressed as

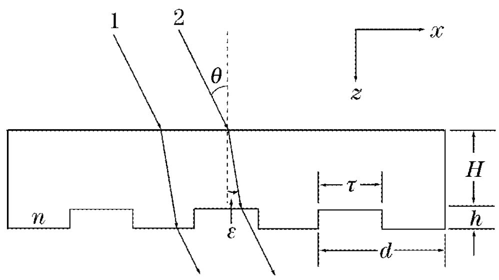

Fig. 1. The plot of rectangular grating.

$$\phi_2 = \frac{2\pi}{\lambda} H \left(\frac{n}{\cos\varepsilon} - \frac{1}{\cos\theta} \right). \tag{2}$$

The phase difference produced by rays 1 and 2 through the grating can be expressed as

$$\Delta\phi = \phi_1 - \phi_2 = \frac{2\pi}{\lambda} h \left(\frac{n}{\cos\varepsilon} - \frac{1}{\cos\theta} \right), \tag{3}$$

apparently, $\cos\varepsilon = \sqrt{n^2 - \sin^2\theta}/n$. The transmissivity function of grating can be expressed as

$$t(x) = \begin{cases} e^{i\phi_1}, (l-1)d < x < l\tau \\ e^{i\phi_2}, l\tau < x < ld \end{cases}, \tag{4}$$

where $l = 1, 2, 3, \cdots$. If Eq. (4) is written as Fourier series form, that is

$$t(x) = \sum_{m=-\infty}^{\infty} c_m e^{imKx}, \tag{5}$$

where $K = 2\pi/d$ is the size of grating vector, $m = 0, \pm1, \pm2, \cdots$ are diffraction orders, and Fourier coefficients can be written as

$$c_m = \frac{1}{d} \int_0^d t(x) e^{-imKx} dx. \tag{6}$$

We define that a monochromatic plane wave with unit amplitude is incident upon the grating at an angle of incidence θ. Apparently, the function can be given as

$$e(x) = e^{i2\pi f_0 x}, \tag{7}$$

where $f_0 = \sin\theta/\lambda$ while the distribution of light vibration in sub-surface of the grating (the exit puple) can be expressed as

$$U_1(x) = e(x)t(x) = \sum_{m=-\infty}^{\infty} c_m e^{i2\pi(f_0 + \frac{m}{d})x}. \tag{8}$$

The distribution $U_2(f_x)$ of diffraction light vibration in viewing screen is a Fourier transform of $U_1(x)$, that is,

$$U_2(f_x) = \sum_{m=-\infty}^{\infty} c_m \delta(f_x - f_0 - \frac{m}{d}), \tag{9}$$

where $f_x = \sin\theta_m/\lambda$, only when $d(\sin\theta_m - \sin\theta) = m\lambda$, Eq. (9) is not zero. In this way, the general expression for diffraction efficiency of all orders of diffracted wave can be written as

$$\eta_m = U_2(f_x)^* U_2(f_x) = |c_m|^2. \tag{10}$$

c_0 and c_m can be calculated from Eq. (6)

$$\begin{cases} c_0 = \rho e^{i\phi_1} + (1-\rho)e^{i\phi_2}, \quad \rho = \tau/d \\ c_{m>0} = \frac{i}{2m\pi}(e^{i\phi_1} - e^{i\phi_2})(e^{-i2m\pi\rho} - 1) \end{cases}. \tag{11}$$

According to Eqs. (10) and (11), we obtain the general expression for diffraction efficiency of rectangular grating

$$\begin{cases} \eta_0 = 1 - 2\rho(1-\rho)(1-\cos\Delta\phi) \\ \eta_{m>0} = \frac{1}{m^2\pi^2}(1 - \cos 2m\pi\rho)(1-\cos\Delta\phi) \end{cases}. \tag{12}$$

We generally adopt the mode of vertical incidence in practical application. From Eq. (3) the phase difference can be obtained as in this time

$$\Delta\phi_0 = \frac{2\pi}{\lambda}(n-1)h, \tag{13}$$

then IRAM can be expressed as

$$\eta_{\pm1,0} = \frac{\eta_{\pm1}}{\eta_0} = \frac{1}{\pi^2} \frac{(1-\cos 2\pi\rho)(1-\cos\Delta\phi_0)}{1 - 2\rho(1-\rho)(1-\cos\Delta\phi_0)}, \tag{14}$$

and the transmissivity (η_{eff}) can be expressed as (we define 1 to be the intensity of incident light beam)

$$\begin{aligned} \eta_{\text{eff}} &= \eta_{-1} + \eta_0 + \eta_{+1} \\ &= 1 - 2\rho(1-\rho)(1-\cos\Delta\phi_0) \\ &\quad + 2(1-\cos 2\pi\rho)(1-\cos\Delta\phi_0)/\pi^2. \end{aligned} \tag{15}$$

It can be seen easily from the process of above deduction that the incident angle of light wave influenced not only the diffraction direction but also the diffraction efficiency, and the positive and negative orders of the same order diffracted wave have the same diffraction efficiency. The result of calculation is slightly different from the result obtained by the vector diffraction theory. The diffraction efficiencies between the positive and negative orders diffracted wave of the same order are not strictly equal at the incident angle $\theta \neq 0$ by rigorous coupled-wave theory. Nevertheless, the difference between two orders is very slight for GOPH of VCD and DVD, whose period is far longer than incident wavelength. We generally adopt the mode of vertical incidence considering the actual requirement in reading, focusing and finding optical disk signal. The results of two orders are same in this time. Consequently, it is reliable enough that the scalar diffraction theory is adopted here.

The LMT refers to a certain minute quantity δ_h that is the deviation between actual groove depth and design value h, consequently IRAM and η_{eff} would bring a certain extent of deviation, respectively. The TMT refers to a certain minute quantity δ_ρ that is the deviation between actual duty cycle and $\rho = 0.5$. In the process of grating manufacturing, the deviation mentioned above cannot be larger than the range of designed destination by controlled δ_h and δ_ρ in order that the mutual matching between the light beam of zero order and those of ±1 orders and the stability of read-write signal are ensured.

In Table 1, the first three items whose data were provided by a company in Japan are used in numerical calculation, the fourth item is the designed value of GOPH whose working wavelength is 780 nm, and the grating material is epoxide resin ($n = 1.567$) in order to be convenient for duplication.

Figure 2 shows a curve of the diffraction efficiency dependence of the groove depth and duty cycle as well as

Table 1. Designed Values of Grating Parameter

$\eta_{\pm1,0}$	η_{eff}	ρ	h (nm)
0.253	≥ 0.87	0.5	293

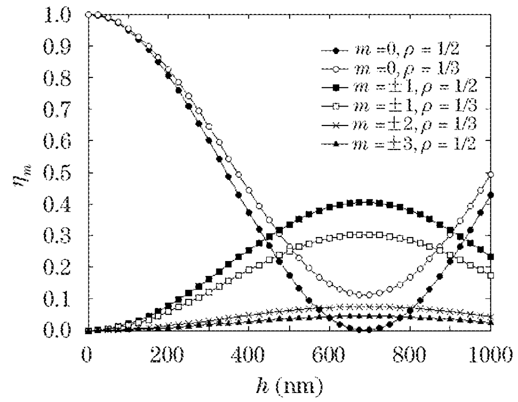

Fig. 2. The relation among the diffraction efficiency, the height of grating groove, duty cycle, and the diffraction order.

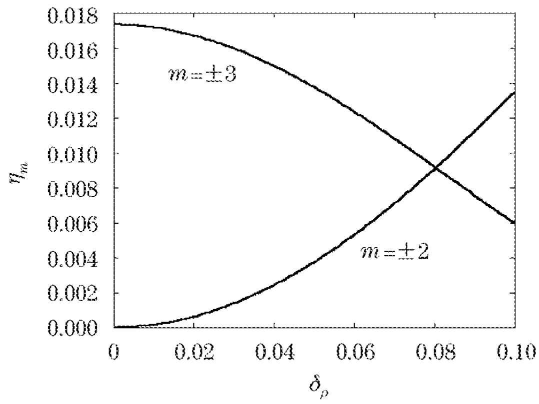

Fig. 3. The relation between δ_ρ and diffraction efficiency in ±2 and ±3 orders ($\delta_h = 0$).

the diffraction order obtained from Eq. (12). From this figure we can see that diffraction efficiencies in the orders of 0, ±1, ±2, and ±3 are varied with the change of groove depth when $\rho = 1/2$ and 1/3. Moreover, the increase and decrease tendency of diffraction efficiency in every order can be seen clearly when the actual groove depth and duty cycle deviate designed values (i.e. there exist LMT and TMT). Figure 3 shows that TMT has effect on the diffraction efficiencies in the orders of ±2 and ±3 when $\delta_h = 0$. It can be seen that TMT makes diffracted wave in the ±2 orders become primary stray light because it approaches closely to the ±1 orders and it has positive relation to TMT. This should be considered on the design of optical pick-up head and the manufacturing of the grating.

We can obtain the groove depth h = 293 nm under condition that we defined $\eta_{\pm1,0} = 0.253$ and duty cycle $\rho = 0.5$ in Eq. (14). The actual groove depth and duty cycle are $h + \delta_h$ and $\rho + \delta_\rho$ respectively because there is mismachining tolerance in existence. So Eqs. (13) and (14) can be changed as

$$\Delta\phi_{0\delta} = \frac{2\pi}{\lambda}(n-1)(h+\delta_h), \tag{16}$$

and

$$\eta_{\pm1,0} = \frac{1}{\pi^2}\frac{(1+\cos 2\pi\delta_\rho)(1-\cos\Delta\phi_{0\delta})}{1-(0.5-2\delta_\rho^2)(1-\cos\Delta\phi_{0\delta})}. \tag{17}$$

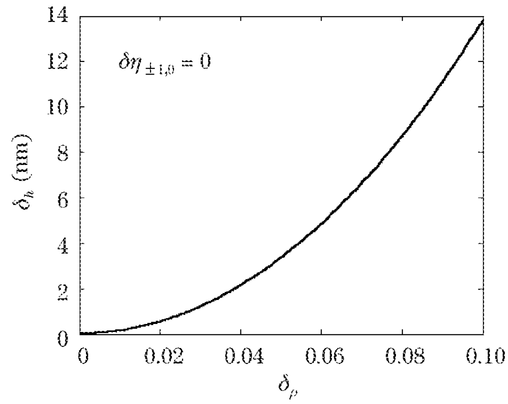

Fig. 4. The compensability between the longitudinal and transverse error of manufacturing.

The result of numerical value from Eq. (17) is shown in Fig. 4. From Fig. 4 we can compensate for the influence of TMT by increasing groove depth (i.e. $h+\delta_h > h$) when LMT and TMT exist simultaneously here, i.e. we can achieve that IRAM is not deviated by complementarity of LMT and TMT, namely, $\delta\eta_{\pm1,0} = 0$ and $\eta_{\pm1,0} = 0.253$ keep invariable. We call this property the complementarity of LMT and TMT of GOPH. Let the horizontal ordinate denote the TMT and the vertical ordinate denote the LMT. As can be seen from Fig. 4, every point in the curve of Eq. (17) corresponds to two values (δ_ρ, δ_h), which can make IRAM not to deviate the designed value. It is significative to make large area GOPH master (convenient for duplicating and cutting) with master mask. Because TMT is inevitable, it is difficult that ratio of the land-to-groove is made 1:1 strictly by master mask exposing and ion beam etching, and this is always one of the technical problems in GOPH. From the results above we can see that the influence of the deviation of the ratio of the land-to-groove from 1:1 on IRAM can be compensated by increasing groove depth. Certainly, this method should not result in more intense interference light coming from oversize diffraction intensity of the ±2 orders, or the interference light is eliminated by filtering.

Figure 5 shows a graphics of the relation among η_{eff}, LMT, and TMT, η_{eff} is 0.927 when the mismachining tolerance does not exist. It can be seen from Fig. 5 that LMT and TMT both have influence on η_{eff}. Firstly, increase in δ_ρ leads to decrease in η_{eff}, the reason is that the deviation of the ratio of the land-to-groove from 1:1 makes the decrease of ±1 more than the increased value of diffraction efficiency of the zero order. Secondly, $\delta_h > 0$ (i.e. actual groove depth is more than the designed one) leads to the decrease in η_{eff}, on the contrary, $\delta_h < 0$ leads to an increase in η_{eff}. In Fig. 2, with groove depth increasing, the diffraction efficiency of the zero order decreases rapidly and the diffraction efficiencies of the ±1 orders increase slowly, therefore $\delta_h > 0$ necessarily results in decrease in η_{eff} and *vice versa*. Consequently, the influence of the deviation the ratio of the land-to-groove from 1:1 on IRAM can be revised by increasing groove depth, however, at the expense of reducing η_{eff}. Nevertheless, according to the data in Table 1, the range of mismachining tolerance determined by Fig. 5 could satisfy the requirement of η_{eff} of the grating, especially when $\delta_\rho \leq 0.05$, the influence

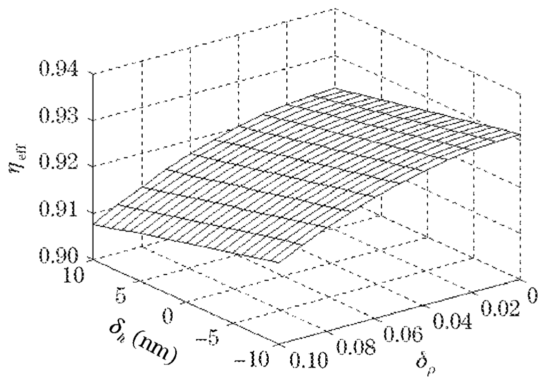

Fig. 5. The effect of the longitudinal and transverse error of manufacture on transmittance.

of the two mismachining tolerances on η_{eff} could be accepted in generally circumstances. If the requirement for high η_{eff} of GOPH is on demand, enhanced coating in incident face in order to overcome the limitation of the method can be used, however, there is no doubt that this method would increase cost.

In summary, numeric analysis is made to the influence of LMT and TMT of the GOPH on η_{eff} and IRAM by using the general expression of diffraction efficiency obtained from the scalar diffraction theory. The paper shows that the scalar diffraction theory and the vector diffraction theory on solving GOPH problem are coincident, and the scalar diffraction theory is reliable. It can be compensated for the deviation resulting from TMT of the IRAM from designed value by increasing groove depth properly. According to the relation among η_{eff}, LMT, and TMT, we can see that both increases in δ_ρ and groove depth lead to decrease in η_{eff}. Consequently, the method of complementation would decrease partial transmissivity, it is necessary to make certain the range of mismachining tolerance in accordance with the actual requirement for η_{eff} to read-write system in the manufacturing of the grating. For GOPH, the complementarity between LMT and TMT is valuable as a reference on the manufacturing of the grating.

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References

1. W. G. Liang, W. H. Zheng, J. H. Xie, E. Z. Liang, L. H. Chen, H. Li, and H. Liu, Chin. J. Semiconductors (in Chinese) **22,** 784 (2001).
2. S. Y. Liu, W. G. Liang, W. H. Zheng, E. Z. Liang, L. H. Chen, J. H. Xie, and D. Z. Zhao, Laser Journal (in Chinese) **22,** 28 (2001).
3. N. Fukunaga and M. Yamamoto, IEEE Trans. Consumer Electron. **43,** 157 (1997).
4. A. Yoshikawa and H. Nakanishi, IEEE Trans. Components, Packing, and Manufacturing Technol. **18,** 245 (1995).
5. H. T. Zhang, M. L. Gong, D. Z. Zhao, P. Yan, R. Z. Cui, and W. P. Jia, Optical Technique (in Chinese) **27,** 217 (2001).
6. H. T. Zhang, M. L. Gong, D. Z. Zhao, P. Yan, R. Z. Cui, and W. P. Jia, Acta Opt. Sin. (in Chinese) **22,** 92 (2002).
7. M. G. Moharam and T. K. Gaylord, J. Opt. Soc. Am. **71,** 811 (1981).
8. M. G. Moharam, E. B. Grann, D. A. Pommet, and T. K. Gaylord, J. Opt. Soc. Am. A **12,** 1068 (1995).
9. Bayanheshig, X. D. Qi, and Y. G. Tang, Acta Phys. Sin. (in Chinese) **52,** 1157 (2003).
10. R. Magnusson and T. K. Gaylord, J. Opt. Soc. Am. **68,** 806 (1978).
11. R. Magnusson and T. K. Gaylord, J. Opt. Soc. Am. **68,** 809 (1978).