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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 goodnes 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[5]; 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 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, $\rho$ is the groove width, $\psi = \tau/d$ 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 $\theta$, $\varepsilon$ is refractive angle. The phase lag produced by ray 1 through the grating can be expressed as

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

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

![Fig. 1. The plot of rectangular grating.](http://www.col.org.cn)
\[ \phi_2 = \frac{2\pi}{\lambda} H \left( \frac{n}{\cos \varepsilon} - \frac{1}{\cos \theta} \right). \]  

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

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

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

\[ t(x) = \begin{cases} e^{i\phi_1}, & (l-1)d < x < lt \tau \\ e^{i\phi_2}, & lt < x < ld \end{cases}, \]  

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

\[ t(x) = \sum_{m=-\infty}^{\infty} c_m e^{imKx}, \]  

where \( K = 2\pi/d \) is the size of grating vector, \( m = 0, \pm 1, \pm 2, \ldots \) are diffraction orders, and Fourier coefficients can be written as

\[ c_m = \frac{1}{d} \int_{0}^{d} t(x) e^{-imKx} dx. \]  

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

\[ e(x) = e^{i2\pi f_0 x}, \]  

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

\[ U_1(x) = e(x) t(x) = \sum_{m=\infty}^{\infty} c_m e^{i2\pi(f_0 + \frac{m}{d}) x}. \]  

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

\[ \sum_{m=\infty}^{\infty} c_m \delta(f_x - f_0 - \frac{m}{d}), \]  

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

\[ \eta_m = \left| U_2(f_x) \right|^2 = |c_m|^2. \]  

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

\[ \begin{align*}
    c_0 &= \rho e^{i\phi_1} + (1 - \rho) e^{i\phi_2}, \quad \rho = \tau/d \\
    c_{m>0} &= \frac{1}{2\pi} (e^{i\phi_1} - e^{i\phi_2}) (e^{im2\pi\rho} - 1).
\end{align*} \]  

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

\[ \begin{align*}
    \eta_{0} &= 1 - 2\rho(1 - \rho)(1 - \cos \Delta \phi) \\
    \eta_{m>0} &= \frac{1}{m^2\pi^2} (1 - \cos 2m\pi\rho)(1 - \cos \Delta \phi).
\end{align*} \]  

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

\[ \Delta \phi_0 = \frac{2\pi}{\lambda} (n - 1) h, \]  

then IRAM can be expressed as

\[ \eta_{\pm 1,0} = \frac{\eta_{\pm 1}}{\eta_0} = \frac{1}{\pi^2} \frac{(1 - \cos 2\pi \rho)(1 - \cos \Delta \phi_0)}{1 - 2\rho(1 - \rho)(1 - \cos \Delta \phi_0)}, \]  

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

\[ \eta_{\text{eff}} = \eta_{-1} + \eta_0 + \eta_{+1} = 1 - 2\rho(1 - \rho)(1 - \cos \Delta \phi_0) \]  

\[ + 2(1 - \cos 2\pi \rho)(1 - \cos \Delta \phi_0)/\pi^2. \]  

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 \( \delta_m \) that is the deviation between actual groove depth and design value \( h \), consequently IRAM and \( \eta_{\text{eff}} \) would bring a certain extent of deviation, respectively. The TMT refers to a certain minute quantity \( \delta_m \) 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 \( \delta_h \) and \( \delta_p \) in order that the mutual matching between the light beam of zero order and those of \( \pm 1 \) orders and the stability of read-write signal are ensured.

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>
<thead>
<tr>
<th>( \eta_{\pm 1,0} )</th>
<th>( \eta_{\text{eff}} )</th>
<th>( \rho )</th>
<th>( h ) (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.253</td>
<td>0.87</td>
<td>0.5</td>
<td>293</td>
</tr>
</tbody>
</table>
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 \( \eta_{\pm 1,0} = 0.253 \) 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

\[
\Delta \phi_{\text{odd}} = \frac{2\pi}{\lambda} (n - 1) (h + \delta_h),
\]

and

\[
\eta_{\pm 1,0} = \frac{1}{\pi^2} \frac{(1 + \cos 2\pi \delta_\rho) (1 - \cos \Delta \phi_{\text{odd}})}{1 - (0.5 - 2\delta_\rho^2) (1 - \cos \Delta \phi_{\text{odd}})}.
\]
of the two machining tolerances on $\eta_{\text{eff}}$ could be accepted in generally circumstances. If the requirement for high $\eta_{\text{eff}}$ 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 $\eta_{\text{eff}}$ 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 $\eta_{\text{eff}}$, LMT, and TMT, we can see that both increases in $\delta_p$ and groove depth lead to decrease in $\eta_{\text{eff}}$. Consequently, the method of complementation would decrease partial transmissivity, it is necessary to make certain the range of machining tolerance in accordance with the actual requirement for $\eta_{\text{eff}}$ 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