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THE OPTICAL CHARACTERISTICS IN THE LAYERS OF COMPACT DISC-RECORDABLE

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Abstract – The optical characteristics of the laser beam in the layers of Compact Disc Recordable (CD-R) has been studied. The optical disk which is compatible with currently used CD-drive consists of transparent polycarbonate (PC) substrate, organic dye recording layer, reflective gold layer, and ultra-violet (UV) cured protecting layer. For proper design of the layer structure, modeling of the optical characteristics in each layer is necessary. The reflection and local absorption of the laser beam energy in the layers of the disk were numerically calculated. The reflection of the disk oscillates with the thickness of dye layer due to the interference in the multilayers. The oscillation magnitude and period depend on the complex refractive index of the material. The energy absorption profile in the recording layer is dependent on the thickness of the layer.

Key words: *CD-R, Optical Disk, The Reflection and Local Absorption, Interference, Complex Refractive Index*

INTRODUCTION

Recently various types of optical disks have been developed and used as the data storage media [Marchant, 1990]. The optical disks can store enormous amounts of digital data in various format depending on the type of the data. The optical disks can be grouped into three categories : read only media (ROM) which reproduce only prerecorded information; write once read many media (WORM) in which new data files can be added; and erasable media which can erase and rewrite data files. Most of these optical disks are constructed in multilayer with various components of materials. We have studied various writable or rewritable organic optical recording media [Chung et al., 1994; Kim et al., 1994, 1995a-c, 1996]. These organic media have several advantages over metallic materials; high recording sensitivity, processability, and nontoxicity, while most of these materials suffer from lack of stability. Among them, CD-R which uses organic dyes for the recording layer is prominent as it can store any personal data in CD-format and can be played in currently used CD player or CD-ROM drive [Pahwa, 1994]. Various texts, pictures, sounds, and moving pictures can be recorded in the disk. The disk can be used for data backup or for test distributions of newly developed software in small amounts.

Fig. 1 shows the structure of the disk. The disk is composed of pregrooved polycarbonate substrate, dye recording layer, gold reflective layer, and UV cured protective layer. The local irradiation of the focused laser beam from high power diode laser (780 nm) induces thermal change of each layer, and this results in permanent marks in the disk, and the reflectivity of the area is decreased. Fig. 2 shows the molecular structure of dyes for CD-R which absorb laser beam energy and convert it to heat energy [Matsuoka, 1990]. The arrangement of the marks with different length is used to record various types of digital data. The reflection difference was detected by the continuous low power laser beam in the drive. To be compatible with CD standard, the disk should have very high reflection (70 percent) at 780 nm, and to achieve this high reflection, proper design of the layers is required. The light reflection and transmission for

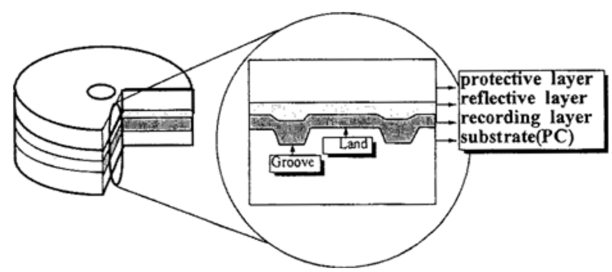
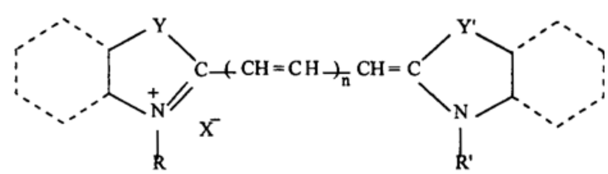


Fig. 1. The structure of CD-R.



Y, Y' : O, S, -CH=CH-, $C(CH_3)_2$ etc
R, R' : Alkyl Group
n : Integer (0, 1, ···, 5)
X^- : Counter Ion (Cl^-, Br^-, I^-, ClO_4^-)

Fig. 2. The general structure of cyanine dyes used for CD-R.

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multilayered film can be numerically calculated by using matrix technique [Bell and Spong, 1978]. This can be used in multilayered optical disks.

In this paper, the optical characteristics of CD-R have been studied by numerical calculations. The light reflection or absorption of the disk were simulated using matrix technique. The effects of complex refractive index and thickness of each layer on the reflection of the disk were studied. The energy absorption rate in each layer of CD-R on recording was calculated by solving energy flux equations [Mansuripur, 1995; Mansuripur et al., 1982]. The modeling for the calculations and simulation results will be described.

LIGHT PROPAGATION IN MULTILAYERS

The light transmission and reflection at normal incidence for multilayer thin film can be calculated by the matrix method. For a plane optical wave propagating in z direction of m layers as shown in Fig. 3, the following Maxwell equations can be applied to the electric and magnetic field components in jth layer:

$$(d^2/dZ^2)E_j(Z)+[2\pi n_j^c/\lambda_o]^2\mathbf{E}_j(Z)=0 \tag{1}$$

$$(d/dZ)E_j(Z)+i(2\pi/\lambda_0)\mathbf{H}_j(Z)=0 \tag{2}$$

where n_j^c is the complex refractive index of jth layer material, and is expressed as

$$n_j^c=n_j-ik_j \tag{3}$$

The incident, reflected, and transmitted electric field amplitudes are related by the following expressions.

$$\begin{bmatrix} E_1^+ \\ E_1^- \end{bmatrix}=\frac{1}{t_1t_2\cdots t_j\cdots t_{m-1}}\begin{bmatrix} 1 & r_1 \\ r_1 & 1 \end{bmatrix}\prod_{j=2}^{m-1}\begin{bmatrix} e^{i\delta_j} & r_je^{i\delta_j} \\ r_je^{-i\delta_j} & e^{-i\delta_j} \end{bmatrix}\begin{bmatrix} E_m^+ \\ 0 \end{bmatrix} \tag{4}$$

$$\delta_j=\frac{2\pi}{\lambda}n_j^cd_j \tag{5}$$

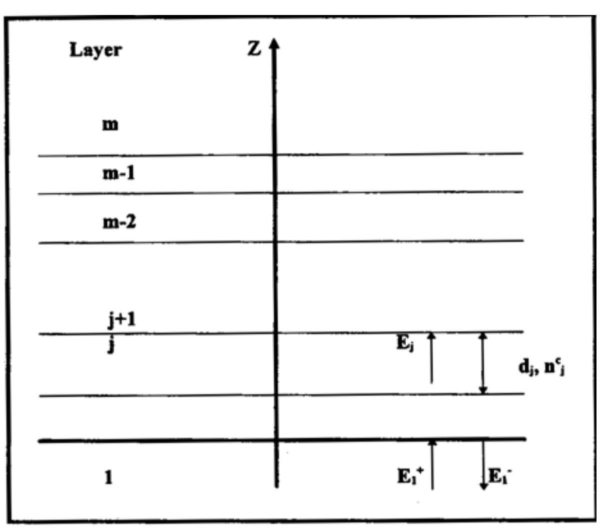

Fig. 3. Labeling convention used for the calculation of the optical properties of the multilayered film.

where d_j is the thickness of jth layer, r_j and t_j are, respectively, the Fresnel reflection and transmission coefficients between jth and (j+1)th layer, i.e.,

$$r_j=\frac{n_j^c-n_{j+1}^c}{n_j^c+n_{j+1}^c} \tag{6}$$

$$t_j=\frac{2n_j^c}{n_j^c+n_{j+1}^c} \tag{7}$$

Eq. (4) reduces to the form

$$\begin{bmatrix} E_1^+ \\ E_1^- \end{bmatrix}=\begin{bmatrix} \alpha_{11} & \alpha_{12} \\ \alpha_{21} & \alpha_{22} \end{bmatrix}\begin{bmatrix} E_m^+ \\ 0 \end{bmatrix} \tag{8}$$

so that the energy reflection and transmission coefficients R and T are given by

$$R=\left|\frac{E_1^-}{E_1^+}\right|^2=\left|\frac{\alpha_{21}}{\alpha_{11}}\right|^2 \tag{9}$$

$$T=\frac{n_m}{n_1}\left|\frac{E_m^+}{E_1^+}\right|^2=\frac{n_m}{n_1}\left|\frac{1}{\alpha_{11}}\right|^2 \tag{10}$$

The rate of energy absorption per unit volume in each layer can be written by

$$q(z)=(d/dz)Re[1/2E(z)H^*(z)] \tag{11}$$

where $H^*(z)$ is the complex conjugate of $H(z)$. The method and equations to obtain above absorption rate are well described elsewhere [Kim et al., 1996].

THE REFLECTIVITY

The reflectivity of CD-R can be calculated based on the equations in the previous section. In CD-R, organic dyes are used as the recording layer. The organic dyes for optical recording media are highly reflective at 780 nm with relatively small absorption. High reflection is required to be compatible with CD player, while the absorption is required for the recording. As these organic dyes are decomposed by light and singlet oxygen, usually a quencher is mixed with dyes. The optical properties of the recording layer strongly depend on its composition. After the dye layer is coated on the PC substrate, the reflective layer is deposited on the dye layer by sputtering. Unlike CD which uses aluminum as the reflective layer CD-R uses gold to increase the overall reflectivity. As CD-R is multilayer structured, the reflection of the disk is very dependent on the optical properties and thickness of the each layer. To understand the effect of refractive index of recording layer material on the reflection of the disk, both real and imaginary part of the index were varied. Fig. 4 shows the dependence of the reflection of the disk on the thickness of the recording layer with various n values and constant k value of the recording layer. The reflection oscillates because of the interference between the light reflected from PC-dye interface and that from dye-gold interface. The figure also shows that as n of the recording layer increases, the reflection oscillates with shorter period and high-

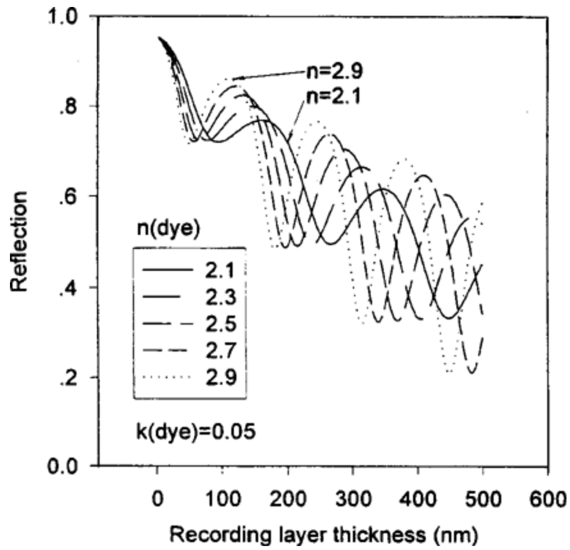

Fig. 4. The effect of n and thickness of the recording layer on the reflection of CD-R.

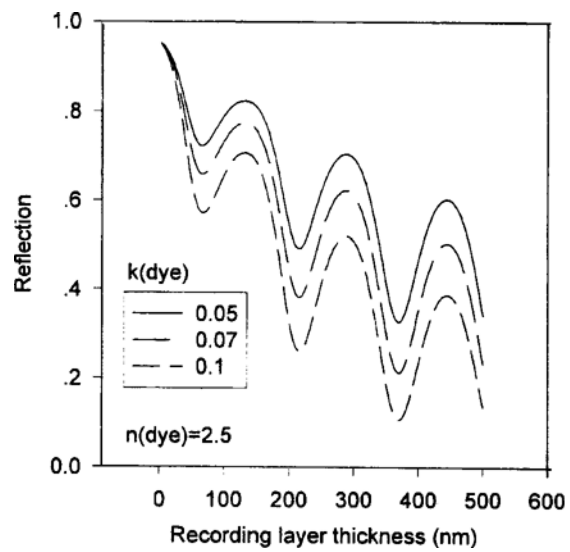

Fig. 5. The effect of k and thickness of the recording layer on the reflection of CD-R.

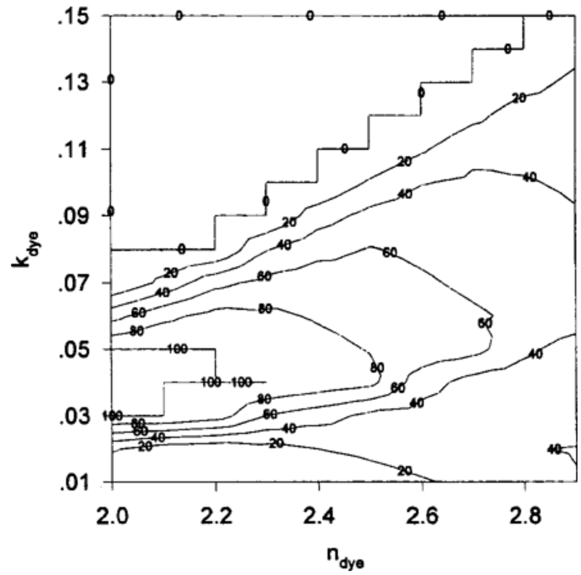

Fig. 6. The contour plot for the number of recording layer thickness values in (n, k) plane of dye satisfying 0.70<R<0.85 in CD-R. The dye layer thickness was varied from 100 to 200 nm by 1 nm step, and the numbers in contour line represent the number of points satisfying the reflection range.

er amplitude. Higher thickness would be necessary for the recording layer with low n.

Fig. 5 shows the effect of k and thickness of the recording layer on the reflection. The figure shows that if n of the layer is constant, the reflection oscillates with the same period, while as k increases, the reflection decreases. This is because k is related with the absorption of the layer.

As CD-R disk has a spiral continuous pregroove on PC substrate, the light reflection from the disk is dependent on the position of the disk. The pregrooved structure which contains wobble signal is used for tracking and positioning during laser writing, and the reflection at the groove area is lower than that at land or blank area. Generally more than 70 % of reflection is required at the blank area of the disk, and the reflection after writing with 11T signal should be more than 65 % at the groove area. For the proper choice of the recording layer, the reflection of the disk needs to be calculated based on the optical properties and layer structure. As the reflection of the disk depends on not only the optical properties but also the thickness of each layer or the groove structure of the disk, the reflection was calculated at the blank area. For the calculation of the reflection, the recording layer thickness at the area was varied from 100 to 200 nm by 1 nm step, and n, k values of the layer were varied from 2.0 to 2.9 and 0.01 to 0.15, respectively. Fig. 6 shows the number of recording layer thickness values in (n, k) plane which satisfy $0.70 < R_{blank} < 0.85$. The maximum limit of the reflection value used here is arbitrary, but if the reflection is too high, not enough energy is transferred to the recording layer, so 0.85 is used as the maximum limit. The figure shows that it is preferable to use dye as the recording layer with n and k value in the range of 2.0 to 2.7 and 0.02 to 0.06, respectively. If the k value of dye is bigger than 0.09 or less than 0.02, the possibility to achieve the above reflection range by controlling the recording layer thickness is very low.

THE ENERGY ABSORPTION RATE

The laser beam energy absorption rate through each layer was calculated based on the model derived by others [Mansuripur et al., 1982]. The model was derived for the energy flux in multilayer disk on recording by diffraction limited Gaussian laser beam incident from the air (air incidence type). The substrate in this model is the last layer of the disk. We adjusted the model to substrate incidence type where the incident laser beam is from the substrate side, so the first layer is the substrate. The thickness of the recording layer was determined based on the reflection values obtained from previous section. First, the energy flux in the layers of CD-R on recording by unit intensity of laser beam was calculated, and then the absorption rate was

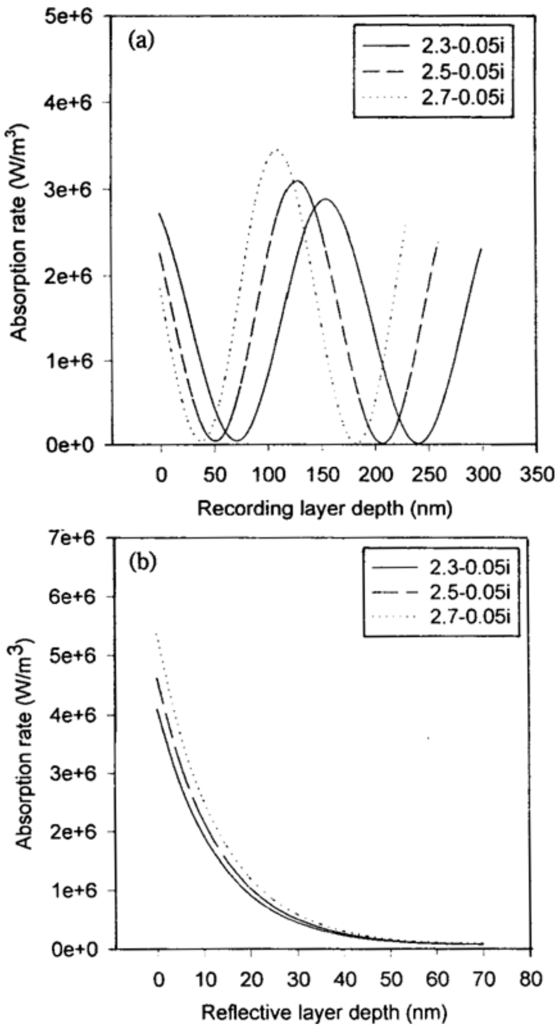

Fig. 7. The effect of refractive index of the recording layer on the absorption rate (a) in the recording layer and (b) in the reflective layer of CD-R on recording with unit intensity of laser beam.

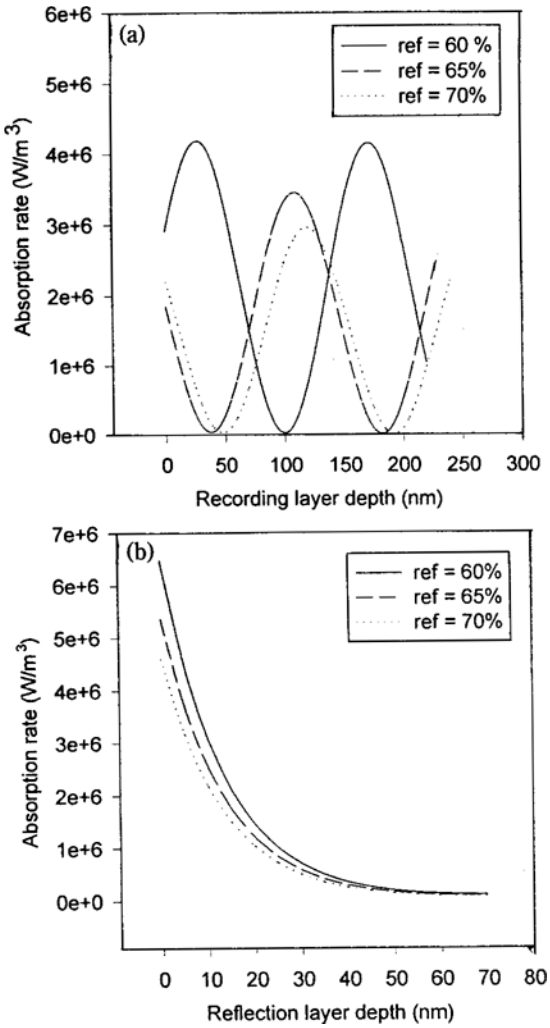

Fig. 8. The effect of recording layer thickness on the absorption rate (a) in the recording layer and (b) in the reflective layer of CD-R on recording with unit intensity of laser beam.

calculated by Eq. (11). Once the absorption profile is determined, the temperature distribution in the layer can be calculated by solving heat conduction equations. In a subsequent paper detailed descriptions will be presented for the modeling and results of the temperature distribution in the layers of CD-R on recording. Here we will only discuss the energy absorption rates and the effects of optical parameters or thickness of each layer on the absorption profiles.

Fig. 7 shows the effect of refractive index on the energy absorption rate in recording (a) and reflective (b) layer of the disk on recording with unit intensity of laser beam. Here only the real part of the refractive index of the recording layer was varied, and the recording layer thickness at the groove area was determined so that the reflection is 65 % . The refractive indices for the recording layer are shown in the figure, and the corresponding thickness is 300, 260, and 230 nm, respectively. The absorption rate in the recording layer is oscillating through the thickness of the layer. As is the case in the reflection, the oscillation period in the layer is approximately equal to $\lambda/2n$, and higher amplitude can be observed with higher n values. With higher k values, higher absorption rate would be observed. The figure also shows that the absorption maxima in the recording layer is observed at the center of the layer in these cases, but the position of the absorption maxima can be changed depending on the layer thickness, as we can see in the next figure. While as the laser light can not penetrate the reflective gold layer, the absorption maxima in the reflective layer is observed at the area which is closest to the recording layer, and the absorption rate decreases exponentially through the layer, and no energy is absorbed in the protective layer. As the substrate is optically transparent, no light energy is also absorbed in the substrate.

Fig. 8 shows the effect of the recording layer thickness on the absorption profile in the layers of CD-R on recording. Here the refractive index of the recording layer is 2.7-0.05i and the thickness of the layer was varied so that the reflection of the area is 60, 65, and 70 %. The recording layer thickness corresponding to these reflection values is 220, 230, and 240 nm, respectively. The figure shows that the position of the absorption maxima can be changed depending on the choice of the recording layer thickness. The absorption rate difference would result in different temperature profile of the area. Thus only some part of the dye recording layer would decompose after laser writing. Though the absorption rate in the recording layer is fairly high, the temperature rise in the layer would be low because of its high thermal conductivity.

CONCLUSIONS

The optical characteristics of the recordable optical disk (CD-R) was studied by numerical calculations. The light interference induced by the multilayer structure of the disk greatly affects both the overall reflection and energy absorption rate in the layers. The reflection of the disk oscillates with the thickness of the recording layer, and the oscillation period and amplitude depend on the refractive index of the layer. To achieve CD compatible disk, it is preferable to use dye as the recording layer with n and k value in the range of 2.0 to 2.7 and 0.02 to 0.06, respectively. The absorption rate in the recording layer oscillates through the layer, and the profile depends on the choice of the recording layer thickness. No energy is absorbed in PC substrate and protecting layer, and the highest absorption rate was observed in the reflective layer which is closest to the recording layer.

NOMENCLATURE

d_j : thickness of the jth layer
$\mathbf{E}_j$: electric field component of a plane optical wave in jth layer
E_1^+ : the incident electric field amplitude for 1st layer
E_1^- : the reflected electric field amplitude for 1st layer
$\mathbf{H}_j$: magnetic filed component of a plane optical wave in jth layer
$\mathbf{H}(z)^*$: complex conjugate of $\mathbf{H}(z)$
k : imaginary part of the complex refractive index
n : real part of the complex refractive index
n_j^c : complex refractive index of the material in jth layer
q(z) : the rate of absorption of energy per unit volume at point z
R_{blank} : reflection at blank area
r_j : Fresnel reflection coefficients at the boundary between jth and the (j+1)th layer material
t_j : Fresnel transmission coefficients at the boundary between jth and the (j+1)th layer material
z : thickness distance in the direction of Z axis

Greek Letters

δ_j : effective optical thickness defined by Eq. (5)
λ_o : wave length

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