Direct modeling of the output parameters of an optical recording

Zhiping Zhou

The relationship between the recorded bit size and write beam characteristics has been analyzed and calculated. A unified formulation for the reflectivity after recording is introduced, and a new analytical description of reflection contrast is established. The effects of read/write beam characteristics on the recording contrast are discussed. The theoretical analysis results are well supported by experiment results.

I. Introduction

The most important optical parameters which are measured during optical recording research and development are reflectivity, contrast, sensitivity, carrier-to-noise ratio, and bit error rate. In a practical case, all these parameters are based on the readout of the light reflecting from the disk surface. In other words, we can easily obtain the values of the above parameters, for example, contrast, by means of certain formulations if we know the value of the reflecting light.

On the other hand, the optical storage math models which were trying to predict the recording quality have their unique output, the temperature profile. The temperature raised by incident laser energy contributes to the change in the recording material reflection property, which varies the readout contrast.

It is clear that there must be some kind of relationship between experimental measurement and theoretical modeling, which makes it possible to simulate directly some of the parameters mentioned above. The main purpose of this paper is to analyze the relationship between laser-induced temperature and recorded bit size and to calculate the functional relation curves between the bit radius and contrast, so that the link between the well established optical recording math model and one of the recording quality parameters, contrast, could be established. In this way, the recording results may be more directly predicted by the math model. Here the contrast is used as an output of the entire process since using the contrast parameter to evaluate the optical recording quality is more convenient and efficient than using the reflectivity parameter.

II. Recording Bit Size Modeling

During a recording process, temperature distribution $T(r,z,t)$ in the recording material can be well described by the heat diffusion equations

$$C(T)\rho(T) \frac{\partial T}{\partial t} = \nabla \cdot J + Q,$$

$$J = -K(T) \nabla T,$$

where $J$ is the heat flux vector, $Q$ is the intrinsic heat source, $C$ is heat capacity, $\rho$ is density, and $K$ is heat conductivity.

For different recording processes, there are different forms of heat diffusion equation. Considering a multilayer in the cylindrical coordinate system $(r,z,t)$, it is convenient to calculate the temperature profile during magneto-optical recording when the following form of heat transfer equations is used:

$$C_n \frac{\partial}{\partial t} T(r,z,t) - K_n \nabla^2 T(r,z,t) = Q(r,z,t),$$

$$\frac{\partial}{\partial z} T(r,z=0,t) = \tau T(r,z=0,t),$$

$$T(r,z=x,t) = T(r=x,z,t),$$

$$T(r,z,t=0) = f(r,z),$$

where $C_n$ is the specific heat of the $n$th layer, $K_n$ is the heat conductivity of the $n$th layer, $\nabla^2 = (\partial^2/\partial r^2) + r^{-1}(\partial/\partial r) + (\partial^2/\partial z^2)$ is the Laplacian operator for circularly symmetric functions, $Q(r,z,t)$ is the power delivered to the unit volume by the laser, $\tau$ is a constant that controls the rate of heat flow from the surface, and $f(r,z)$ is the initial temperature distribution. But during phase change recording it is necessary to use the

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heat transfer equations into which the moving boundary conditions are introduced:

\[ -k(1) \frac{\partial T^*(1)}{\partial z} = HT^*(1), \quad z = 0, \tag{7} \]

\[ \frac{\partial^2 T^*(1)}{\partial z^2} + \frac{\partial T^*(1)}{\partial r} + \frac{\partial^2 T^*(1)}{\partial z^2} + \frac{Q(r,z,t)}{k(1)} = \frac{\partial T^*(1)}{\partial t}, \quad 0 < z < z^*, \tag{8} \]

\[ \frac{\partial^2 T(j)}{\partial z^2} + \frac{\partial T(j)}{\partial r} + \frac{\partial^2 T(j)}{\partial z^2} + \frac{Q(r,z,t)}{k(j)} = \frac{\partial T(j)}{\partial t}, \quad z(j-1) < z < z(j), \quad j = 1,2,3,\ldots,n-1. \tag{9} \]

\[ T^*(1) = T(1) = T_m \text{ (melting temperature)} \quad z = z^*(t), r = r^*(t), \tag{10} \]

\[ k(1) \frac{\partial T^*(1)}{\partial r} - k^*(1) \frac{\partial T^*(1)}{\partial r} = \rho L \frac{dr}{dt}, \quad r = r^*(t), \tag{11} \]

\[ k(1) \frac{\partial T(1)}{\partial r} - k^*(1) \frac{\partial T(1)}{\partial r} = \rho L \frac{dz}{dt}, \quad z = z^*(t), \tag{12} \]

\[ T(j) = T(j + 1) \quad z = z_j, \quad j = 1,2,3,\ldots,n-1, \tag{13} \]

\[ k(j) \frac{\partial T(j)}{\partial z} = k(j + 1) \frac{\partial T(j + 1)}{\partial z}, \quad z = z_j, \quad j = 1,2,3,\ldots,n-1. \tag{14} \]

where \( T = T(r,z,t) \) represents the time-space distribution of the temperature field in the multilayer medium, \( H \) is the convective coefficient, \( L \) is the latent heat of fusion, \( Q \) is the intrinsic heat source, and \( dp/dt \) and \( dz/dt \) are velocities of the phase change boundary in radial and axial directions. In this group of equations, the moving boundary layer, i.e., the molten absorptive layer, is designated by an asterisk.

In addition, other boundary conditions are as follows:

\[ T|_{t=0} = 0; \tag{15} \]

\[ \frac{\partial T}{\partial r} |_{r=0} = 0; \tag{16} \]

\[ T|_{t=t^o} = 0. \tag{17} \]

These are the basic equations by means of which the bit recording process is modeled.

To record a bit on a film, the film should be heated by a finely focused laser spot. For a TbFe magneto-optic film, the temperature should be over 100°C where the coercivity drops to several hundred oersteds, and the bias field which is larger than the coercivity of TbFe at this elevated temperature is then applied to form a bit. For a Te-based phase change film, the temperature should be over 450°C so that the phase change could happen to form a bit.

Because of the Gaussian distribution of the intensity of the laser spot, the temperature along the radial axis gradually declines from the heated area center to infinity. This usually produces an unclear edge of recorded bits and makes the problem more complicated. To simplify it, we assume that there is a radius of isotherm inside of which the reflectivity is changed due to the thermooptic effects (including magnetooptic and phase change processes) and outside of which the reflectivity remains the same as before heating. This isotherm may be defined as the edge of the recorded bit. In our work, we used a single Te layer deposited on a glass substrate and defined the isotherm of 450°C as the edge of the recorded bit. As assumed, above this temperature the film is melted, the phase change takes place, and then a bit which corresponds to a circular area higher than 450°C is formed.

Using the well established math model equations (7)-(17), the bit size recorded by the short pulse laser beams (Fig. 1) have been calculated. Figures 2 and 3 show the relationship between input laser power and the recorded bit radius, corresponding to the input optical pulse waveforms [Figs. 1(A) and (B)], respec-
Fig. 3. Laser power dependence of melted radius with waveform (B).

Fig. 4. Effects of incident beam distributions on the temperature-space characteristics.

The reflectivity before recording $R_b$ can be taken directly from manufacturers, but the reflectivity after recording $R_a$ is more complex. Since the information bit will be recorded by a finely focused laser beam and the measurement of reflectivity is also made with a focused beam, a unified formulation for the reflectivity after recording can be defined as follows:

$$R_a = R_a(L, G),$$

where $L = L(r, T)$ is the recorded bit area, $G = G(r, T)$ is the grey scale function in the recorded area, $r$ is the space vector within the recorded area, and $T$ is the temperature. By assuming that the recorded area is uniform, we set $G(r_m, T_m) = G_0$, which keeps $G(r, T)$ on a constant level within melting radius $r_m$ and melting temperature $T_m$. Now $R_a$ becomes the function of the recorded bit area. Moreover, assuming that the recorded bit has a round shape and recalling from the last section that the radius of an isotherm was provided, $R_a$ becomes the function of the radius of a recorded bit only.

Because the Gaussian intensity distribution at the read/write beam focus plane has the form

$$I = \left[\frac{p(t)}{\pi r_0^2}\right] \exp\left[-\left(\frac{r}{r_0}\right)^2\right],$$

where $r_0$ is the exp(-1) E-field point and $p(t)$ is the instantaneous power, the total intensity at the focus plane before recording will be the integration of the Gaussian intensity in the entire focus plane:

$$I_b = \left[\frac{p(t)}{\pi r_0^2}\right] \int_0^{2\pi} \int_0^{r_0} \exp\left[-\left(\frac{r}{r_0}\right)^2\right] r dr d\phi,$$

and the reflecting intensity from the focus plane after recording will be

$$I_a = \left[\frac{p(t)}{\pi r_0^2}\right] \int_0^{2\pi} \int_{r_m}^{r_0} \exp\left[-\left(\frac{r}{r_0}\right)^2\right] r dr d\phi,$$

where $r_m$ is the radius of the chosen isotherm. In the
above formulation, it is assumed that the grey scale of the unrecorded surface is zero and that of the recorded area is one.

Using the contrast definition and formulation above, the functional curve between the melted radius and recording contrast with a different distribution of a readout spot as a parameter has been calculated as shown in Fig. 5. From the curve, it is clear that the smaller the readout spot and the bigger the recorded bit size, the higher the reflection contrast. This is in good agreement with the real situation.

Combining Figs. 2 (or 3) and 5, a relationship between read/write characteristics and reflection contrast can be easily described; that is, for a group of given writing parameters, such as input power, beam size, time interval, and material properties, through the math model established above, a corresponding readout contrast can be expected. Since both curves 2 and 5 are obtained through computer simulation, it is possible to evaluate and predict the optical storage quality without a real recording process.

IV. Experimental Results

A number of write and read experiments have been performed by using a specially designed static recording experimental device shown in Fig. 6 to support the calculated results. In the device arrangement, the AOM can adjust the optical pulse width from 20 ns to infinity with a waveform shown in Fig. 1(A) and output either a single pulse or a pulse string with any length. The argon laser cw output at 5145 Å has a maximum of 2 W, and the spot on the film surface was controlled with the $r_0$ around 3500 Å. The detecting circuit can distinguish a reflectivity change as low as 1%. The read/write processes can be well monitored through both a detecting circuit and eyepiece. During the experiments, a monolayer Te-based film deposited on a glass substrate was illuminated by the argon laser beam with different intensity distributions, pulse widths, and laser energies. The experimental relationship between the contrast and writing power and pulse width is shown in Fig. 7. Note that from the curve with a 100-ns pulse width the contrast varies from 0.07 to 0.17, while the average write power changes from 5.5 to 7 mW. Combining Figs. 2 and 5, a similar numerical result is obtained. In addition, the relationship between the recording laser power and recorded bit size is well supported by the SEM observation.
V. Conclusions

We have already analyzed the relationship between the read/write beam characteristics and the reflection contrast theoretically and experimentally. A direct link between the optical recording math model and the contrast has also been established. Following this work, a more meaningful computer model of the optical recording could be made to predict the behavior of the actual recording process. The results can also be used for examining other recording parameters such as the optical recording sensitivity and the recording threshold, which provide some useful theoretical basis for optical recording.

References


