Simulating Readout Signals of 3D Geometrical Pits/lands and Surface Defects

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ABSTRACT

Higher NA optical pick-ups (OPUs) are being applied in optical storage system for high capacity. As the vector characteristics of the laser beam in high NA OPU play an important role in the interaction between the disc information layer and laser beam, simulations based on both vector diffraction theory and rigorous calculation of Maxwell’s equations are becoming more and more important. They not only provide accurate and reliable simulation results, but also make it possible to investigate many other interesting topics e.g. the feasibility of using polarized light to increase storage density of optical discs. In this paper, a software package based on three-dimensional finite-difference time domain algorithm (3D-FDTD) is introduced to simulate readout signals. It can be used to simulate the reflection pattern for three dimension geometrical pits accurately. Moreover, because it can interface with optical design program ZEMAX, the simulation can be done for different light paths and in the presence of surface defects, which is very useful for analyzing and evaluating a practical OPU. The features of this software are expected to help explore new disc formats, understanding signals in servo path and data path, and furthermore designing a new optical pick-up etc.

Keywords: optical storage, simulation, 3D FDTD, vector diffraction, surface defects

1. INTRODUCTION

To increase capacity of optical storage via optical system, either shorter wavelength or higher NA optical system has to be conducted. For both CE application and PC data application, considering cost issue, blue light is probably the shortest wavelength being used. Consequently, to further increase capacities, a further increase in NA will be required. In a high NA optical pick-up (OPU), vector characteristics of laser beam plays an important role in the interaction between the disc information layer and laser beam. Therefore, the scalar diffraction approach\textsuperscript{1} is not sufficient for exploring new disc formats and understanding signals in servo path and data path. Rigorous simulations on diffraction of the optical field on the information layer are necessary. Up to now, various numerical techniques, such as the rigorous coupled wave analysis\textsuperscript{2}, the boundary element method\textsuperscript{3}, the integral method\textsuperscript{4, 5}, the finite difference frequency domain method\textsuperscript{6}, etc., have been proposed to simulate diffraction on the information layer of an optical disc. Among all, the finite-difference time-domain (FDTD) method\textsuperscript{7-10} offers accurate solutions to investigate the diffraction field near the information layer with arbitrary geometry.

In this paper, an accurate three dimensional (3D) vector simulator incorporating a 3D FDTD algorithm for linearly dispersive material is proposed and developed to simulate the readout of the OPU of an optical disc system as Figure 1. The 3D simulator offers the design of the realistic configuration of an OPU, including various kinds of possible optical elements (e.g. lenses, PBS, wave-plates, etc.) with finite aperture and various geometries. The 3D geometry of the information layer (pits and lands) as well as the finite impedance and the dispersive characteristic of the metal coating are taken into account. Furthermore, typical optical and mechanical defects on a realistic optical disc, e.g. the tilt, and disc surface defects as black dot, scratch, etc., are also included in the model. The simulation of the readout process mainly involves the far-field to near-field transformation (and the near-field to far-field transformation), the near-field calculation, the physical optical propagation (POP) and the calculation of the readout signal. These parts are calculated using diffraction theory, the 3D FDTD algorithm, the POP analysis of...
ZEMAX and the integration method, respectively. Scanning of the focused light along the track can be simulated, and the near-field and far-field distributions as well as the readout signal can be obtained. With functionalities of realistic modeling and vector simulation, our simulator is helpful in understanding signals in servo path and data path, and furthermore designing a new OPU and novel disc formats, etc.

Figure 1: Schematic diagram of the typical readout for an optical disc system

2. PRINCIPLE OF 3D FDTD ALGORITHM

In a typical optical storage system, the reflection layer is usually made of a metal (e.g. aluminum) whose imaginary part of the refractive index is greater than real part at the working frequency (denoted by $\omega$). This indicates that the permittivity of the metal has a negative real part. To guarantee the stability of the FDTD algorithm, the Drude model is adopted in the FDTD algorithm. The Maxwell equations in Drude model are written as:

$$\frac{\partial E}{\partial t} = \nabla \times \vec{H} - J_p,$$

(1)

$$\frac{\partial H}{\partial t} = -\frac{1}{\mu_0} \nabla \times \vec{E},$$

(2)

$$\frac{dJ_p}{dt} = \varepsilon_0 \omega^2 \vec{E} - \gamma_0 J_p,$$

(3)

where $J_p$ denotes the polarization current density, $\gamma_0$ denotes the damping coefficient, $\omega_p$ denotes the plasma frequency, $\varepsilon$ denote the permittivity, and $\mu_0$ denote the permeability in vacuum. Note that when $\omega$ is small enough (which means a low frequency light is incident), the left hand side of Eq. (3) can be negligible. Thus $J_p$ is linearly related to $\vec{E}$, with $J_p = \left(\varepsilon_0 \omega^2 / \gamma_0 \right) \vec{E}$. In this case, Eqs.(1)-(3) degenerate to the common formula for modeling metals with a single parameter of conductivity $\sigma = \varepsilon_0 \omega^2 / \gamma_0$. In the Drude model, media is considered to be isotropic.

Eqs.(1)-(3) are used to treat the field in both the dielectric substrate and the metal. In the dielectric substrate, $J_p$ and Eq. (3) are negligible. $\varepsilon$ is set to the permittivity of the dielectric substrate, as $\varepsilon = n_r^2 \varepsilon_0$, where $n_r$ is the refractive index of the dielectric substrate, and $\varepsilon_0$ denote the permittivity in vacuum. In the metal, $\varepsilon$ is simply set to $\varepsilon_0$, and the relative permittivity of the metal is obtained from both Eq. (1) and (3) as (taking the time dependence $e^{-\omega_t}$ for $\vec{E}$, $\vec{H}$ and $\vec{J}_p$),

$$\frac{\varepsilon(\omega)}{\varepsilon_0} = \varepsilon_r + i\varepsilon_i = \left(n_r + in_i\right)^2 = 1 - \frac{\omega_p^2}{\omega^2 + i\gamma_0 \omega},$$

(4)
Given the complex refractive index \( n_r + i n_t \) of the metal at the working frequency \( \omega, \gamma_0 \) and \( \omega_p \) can be obtained with Eq. (4).

The calculation region is divided into a total-field region and a scatter-field region (see Figure 2). It is discretized in the Yee grid cells. The PML (perfectly matched layer) boundary is adopted in the algorithm. The source field is introduced on the source boundary with parameters obtained from the far-field to near-field transformation, and the electromagnetic field distribution can be obtained through iterating Eqs. (1)-(3) in the time domain. After the FDTD iteration converges to a steady-state condition, the field at the sampling plane (see Figure 2), which lies in the scattering region, is sampled by integrating in time the transverse scattered field over the last complete period of the incident signal, which is used in the near-field to far-field transformation.

![Figure 2: Diagram of the FDTD calculation region](image)

**Figure 2: Diagram of the FDTD calculation region**

**Figure 3: The software architecture of the simulator**

### 3. SOFTWARE ARCHITECTURE AND FEATURES

The architecture of the simulator mainly involves three parts, the configuration setup, the readout simulation and the result analysis. As shown in Figure 3, a user first defines an OPU, including the incident optical path, the collective...
optical path, the information layer and the defects on the disc surface. After that, the light path is divided into various calculation sections, each of which would be calculated with an appropriate algorithm (the FDTD, the diffraction theory, or the POP analysis by ZEMAX). The focused spots along the track are also determined, together with other simulation parameters. The simulation is carried out from one focus spot to another in sequence. At each time step, the vector field is propagated from one section to another, with the output field of the former section being the input field of the next one. After the simulation started, the calculation result can be examined at any time, the full-vector near field and the vector far field distribution are visualized 3-D graphically, and the readout signal collected by a user-defined detector is calculated. Various signals (e.g. the CA signal, the push-pull signal, etc.) can be plotted as the focus spot moves along the track.

Compared with scalar diffraction modeling, 3D geometrical modeling and the FDTD algorithm are capable of simulating the diffraction of a focus vector field (typically polarized) on the information layer of an optical disc. The present simulator is expected to help design of an optical disc with complex information structure and smaller feature size. Incorporated with the most popular and powerful optical design package, ZEMAX, the present simulator is able to calculate the performance of most OPU configurations, which could help design of new OPU and new disc formats with better performance. Another feature of the present simulator lies in the consideration of various defects existing in practical discs. With this consideration, impact of some defects on the readout signal of an optical disc system can be studied.

4. SIMULATION RESULTS

The simulations on the known optical storage system are used to test this algorithm qualitatively and its features. A practical DVD system with disc surface defects is analyzed in the present simulator, and the main parameters of this system are listed in Table 1. The information layer of the disc adopts the typical periodic structure with a unit cell of a biaxial structure of pits. The incident field at the objective lens is set to be a circular polarized Gaussian beam whose waist size equals to the aperture size of the objective lens. Typically, the calculation time for one intensity distribution profile is about 30min with a 2.2GHz/512M PC.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Wavelength</td>
<td>650 nm</td>
</tr>
<tr>
<td>NA</td>
<td>0.6</td>
</tr>
<tr>
<td>Thickness of substrate</td>
<td>0.6 mm</td>
</tr>
<tr>
<td>Channel bit length (T)</td>
<td>133 nm</td>
</tr>
<tr>
<td>Min. pit (land) length (3T)</td>
<td>400 nm</td>
</tr>
<tr>
<td>Max. pit (land) length (14T)</td>
<td>1866 nm</td>
</tr>
<tr>
<td>Track pitch</td>
<td>320 nm</td>
</tr>
<tr>
<td>Refractive index of substrate</td>
<td>1.6</td>
</tr>
<tr>
<td>Refractive index of metal</td>
<td>1.5 + 7.8i</td>
</tr>
<tr>
<td>Side wall angle of pit</td>
<td>45°</td>
</tr>
<tr>
<td>Pit depth</td>
<td>105 nm</td>
</tr>
<tr>
<td>Pit width</td>
<td>400 nm</td>
</tr>
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</table>

Figure 4-7 show the baseball patterns for various discs (perfectly or with defects). In those figures, the horizontal axis is the track direction, and the vertical axis is the radial direction. The white circles in the figures are the apertures of the objective lens. The fields outside the white circles present the high diffraction orders, and will be truncated when calculating the readout signals. Figure 4 shows the baseball patterns of this DVD system, while no defects exist.
Figure 4: The baseball pattern with no defects, while the laser focused on the center of (a) a 3T pit, (b) a 3T land, (c) a 14T pit and (d) a 14T land.

Figure 5: The baseball pattern with a black dot, while the laser focused on the center of (a) a 3T pit, (b) a 3T land, (c) a 14T pit and (d) a 14T land.

Figure 6: The baseball pattern with a tilt along track direction, while the laser focused on the center of (a) a 3T pit, (b) a 3T land, (c) a 14T pit and (d) a 14T land.

Figure 7: The baseball pattern with a scratch, while the laser focused on the center of (a) a 3T pit, (b) a 3T land, (c) a 14T pit and (d) a 14T land.
Figure 5 shows the baseball patterns, while a black dot is located on the surface of the substrate. The black dot is considered here as an area with circular shape (radius: 0.7 mm) and low transmittance (transmittance: 0.05). This black dot is located at the up-right corner. Note that the readout beam will encounter this black dot twice (one is in the incidence path; the other is in the reflection path). Thus, we can clearly see that there is an indentation in every diffraction order at the bottom-left corner (cf. Figure 5 (a)-(c)). This is because the incident beam is truncated with the black dot, then diffracted to the opponent side by disc structures. These simulation results match well what we see in related experiments.

Figure 6 and 7 show the baseball patterns, while a tilt (1°) of the disc along the track direction and a scratch on the substrate is present, respectively. The scratch is considered as the undulation of the substrate surface. It is difficult to simulate the light scattering from an arbitrary rough surface. For simplicity, the scratch is treated as a grid surface in ZEMAX in our simulator. The geometrical optics approximation (ray tracing) is adopted here. This approximation requires that the curvature of the scratch surface at every point should be much larger than the wavelength of the incident light. In Figure 7, the scratch is located at the right side.

In the following discussions, we use our algorithm to simulate a BD-ROM system. The parameters of this system are listed in Table 2.

Table 2: Parameters of a BD-ROM system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Wavelength</td>
<td>405 nm</td>
</tr>
<tr>
<td>NA</td>
<td>0.85</td>
</tr>
<tr>
<td>Thickness of substrate</td>
<td>0.1 mm</td>
</tr>
<tr>
<td>Channel bit length (T)</td>
<td>74.5 nm</td>
</tr>
<tr>
<td>Min. pit (land) length (2T)</td>
<td>150 nm</td>
</tr>
<tr>
<td>Max. pit (land) length (8T)</td>
<td>596 nm</td>
</tr>
<tr>
<td>Track pitch</td>
<td>320 nm</td>
</tr>
<tr>
<td>Refractive index of substrate</td>
<td>1.55</td>
</tr>
<tr>
<td>Refractive index of metal</td>
<td>0.7 + 4.55i</td>
</tr>
<tr>
<td>Side wall angle of pit</td>
<td>50°</td>
</tr>
<tr>
<td>Pit depth</td>
<td>65 nm</td>
</tr>
<tr>
<td>Pit width</td>
<td>150 nm</td>
</tr>
</tbody>
</table>

The MTF (Modulation Transfer Function) of this system is calculated and plotted in Figure 8.

![MTF Graph](image)

Figure 8: The simulated MTF of the BD-ROM system

Three merit parameters, namely, the modulation MOD, Resolution RES, and the asymmetry ASY, are usually used to describe the quality of the whole system, and they are defined as follows
where $I_{mH}$ and $I_{mL}$ are the maximal and minimal detector signals for a $nT$ pit-land structure, respectively. The calculated values of $MOD$, $RES$ and $ASY$ in this system are 0.8326, 8.09% and 9.95%, respectively. These simulation results show the features of this software are useful for analyzing and evaluating a practical system, while the 3D geometry of pits is taken into consideration.

5. CONCLUSION

One 3D vector simulation software incorporating a 3D FDTD algorithm for linearly dispersive material has been proposed, developed and tested with known optical storage systems. 3D realistic configurations of a complete OPU can be defined in the simulator as well as the 3D geometries of the information layer of an optical disc. Combined with ZEMAX, the software can be used to investigate the signals in servo path and data path, and furthermore to design a new OPU and novel disc formats, etc.

REFERENCES