Modeling and experimental study of light scattering effects in optical data storage systems

PhD thesis

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Introduction

Department of Atomic Physics of Budapest University of Technology has wide scale industrial relationships and international research co-operations. Previous projects accumulated significant experience in the field of optical data storage and many diploma and PhD thesis was written in different topics. Topic of current PhD thesis was defined by two of these co-operations. First one is an agreement with Philips Hungary on developing and solving manufacturing problems of CD and DVD drives. Second is a European Union research project called MICROHOLAS, which targeted to develop a mass storage optical device working on microholographic principles.

The most widespread optical data storage systems (CD, DVD and Blu-ray) are bit organized, and their working principle has not changed since the development of the CD. A laser beam focused to diffraction limit writes the coded data into the light sensitive storage layer of a spinning disc. During readout the change of the reflected light from the data layer is detected. The microholographic date storage system is an improved version of the CD-type systems. Microholograms are created by two counterpropagating, highly focused beams. Microholograms are recorded in a photopolymer as permittivity change of the material due to photopolymerization. The read beam is reflected from the microhologram to reconstruct the signal. There is a significant difference compared to the common optical formats: microholographic data storage is a volume based, multilayer recording technique, which strongly improves the storage capacity. The increasing level of development induces a growing demand for the development of models that accurately describes the microholographic writing and reading process, and suited to optimize the system.

Objectives

One of the most frequent problems in optical data storage systems is the noise caused by different light scattering effects. My work aimed to study light scattering effects with new models, to experimentally prove modeling results, and applying models on optical data storage systems already available and under development.

I studied CD and DVD systems, and in the project MICROHOLAS I investigated the microholographic data storage system, what is a bit oriented holographic mass storage system.

In my dissertation I present the microholographic system model, the study of nonlinear and nonlocal behavior of the photopolymer storage material, and propose using confocal filtering to significantly decrease the crosstalk between layers and holograms. I present my results on studying surface defects of objective lenses used in optical data storage.

I summarize the results in four thesis points as follows.

New scientific results

1. I established the optical model of the microholographic data storage system. I calculated the light scattering on microholograms based on the perturbation theory of electromagnetic scattering. I showed that in case of the materials used in practice the Born approximation can be used to calculate the diffracted electromagnetic field. The whole model is three dimensional and the Bragg effect in thick hologram is taken into account. I described the optical system by ideal lenses and apertures, and calculated the propagation of beams by methods of Fourier optics. Using the model it is possible to calculate the diffracted electromagnetic field from any bit configuration, and capable of modeling the readout of recorded bit sequences. [1, 4, 5, 9]

2. I established a new model of the photopolymer based holographic storage materials, which take into account the nonlinear and nonlocal properties of the material. I showed that the nonlinear property of the photopolymer material is not enough to describing the behavior of the material. By comparing the model and the results of experiments I showed that monomer diffusion in photopolymers must be taken into account to properly describe the hologram recording process. The diffusion equation describes changing of monomer and polymer concentration in photopolymers, and accurately models recording. I showed that the diffusion equation can be simplified if it is applied on the microholographic system. Changing of the monomer concentration can be described by convolution of the initial monomer concentration and a Gauss function. Simulation results what takes diffusion into account fit well to the experiments. [6, 7, 8, 9]

3. I showed that crosstalk between holograms and layers can be significantly decreased in the multilayer microholographic data storage system by using confocal filter. I used the microholographic system model to create statistics from the readout of thousands of different bit configurations. From these results I calculated the signal to noise ratio and bit error rate of the microholographic data storage system. I proved that confocal filtering can improve bit error rate and significantly decrease layer distance, what results in higher data density and storage capacity. Experiments verified the simulation result. I used the model of the data storage system to calculate important tolerances of the system like track error and focus error. From results of these tolerance calculations I determined the optimal position and size of the confocal filter. I used optical design program to design a confocal filtering module, what was built into the demonstrator of the microholographic data storage system. [4, 5]

4. I created three different complexity models to describe the surface errors of objective lenses used in optical data storage. These are the simple geometrical optics approximation, the Fourier optics approximation and the real ray tracing based diffraction model. Encircled energy in Airy disk of an objective lens with an arbitrary surface error can be calculated from all of these models. We built a measurement tool to qualify objective lenses. This tool can measure the encircled energy within the Airy disk. I compared the results of the three models to the measurements of objective lens with surface errors. I found, that the real ray tracing based diffraction model fit well to the experimental results, and malfunction of the system can be forecasted. [1, 2, 3]

Utilization of results

My colleagues used my simulation software and codes in further investigation of the microholographic data storage system. Experience on the material model was taken into account during modeling of other holographic data storage systems. I designed a confocal filter module for the microholographic data storage system, which was successfully used in the demonstrator system. We built a measurement tool to qualify objective lenses with surface errors. This measurement setup was used by Philips Hungary to solve manufacturing problems.

Publications related to the thesis points

1. Nagy Zsolt, „Mi a titka? – Optikai adattárolás”, *Természet Világa*, 138. évf. 2. sz., (2007 február).

2. Zs. Nagy, P. Koppa, Gy. Nádudvari, E. Dirix and P. Richter, „Modeling air inclusions in high-performance objective lenses”, *Proc. SPIE*, **5249**, pp. 703-709, (2004)

3. Zs. Nagy, P. Koppa, F. Ujhelyi and P. Richter, „Modelling local defects on the surface of high performance objective lenses”, *J. Opt. A: Pure Appl. Opt.*, **7**, 265-270, (2005).

4. Zs. Nagy, E. Dietz, S. Frohmann, S. Orlic and P. Koppa, „Theoretical modeling of multilayer microholographic recording and readout”, *Conference on Laser and Electro Optics 2005*, Proceeding pp. 186- , Poster presentation, (2005).

5. Zs. Nagy, P. Koppa, E. Dietz, S. Frohmann, S. Orlic and E. Lőrincz, „Modeling of multilayer microholographic data storage”, *Appl. Optics*, **46**, 753-761, (2007)

6. Zs. Nagy, P. Koppa, E. Dietz, S. Frohmann and S. Orlic, „Modeling material saturation effects on microholographic recording”, *Conference on Innovative Mass Storage*

Technologies, Proceedings pp. 279-280, Poster presentation, (2006).

7. Zs. Nagy, P. Koppa, F. Ujhelyi, E. Dietz, S. Frohmann and S. Orlic, „Modeling material saturation effects in microholographic recording”, *Optics Express*, **15**, 4, pp. 1732-1737, (2007).

8. P. Koppa, Zs. Nagy, B. Gombkötő, F. Ujhelyi, E. Lőrincz, E. Dietz, S. Frohmann, and S. Orlic, " Modeling Multilayer Microholographic Storage with Nonlocal and Nonlinear Storage Material Behavior," in *Optical Data Storage*, OSA Technical Digest Series (CD) (Optical Society of America, 2007), paper MB3.

9. B. Gombkötő, Zs. Nagy, P. Koppa, E. Lőrincz, „Modeling high density microholographic data storage: using linear, quadratic, tresholding and hard clipping material characteristics”, *Optics Communications* (accepted, 2008)