New Models and Tools for Researching Holographic Data Storage Systems

PhD Thesis

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Introduction

Holographic data storage aims storing digital information in holograms. This is a promising alternative of present optical data storage devices. Holographic data storage systems display the information in form of 2-dimensional images, accordingly they belong to the page-organized optical memories. A spatial light modulator displays the information as black-and-white or gray-scale images where the brightness of the pixels represents the data. These images are usually Fourier transformed and holographically recorded in suitable storage materials. During the readout, the holograms are reconstructed and the obtained images are processed by a detector array. Two key quantities are used for the characterization of a holographic data storage system. The first is the data density that expresses the amount of bits in a given unit of surface or volume. The second is the raw Bit Error Rate (BER) that indicates the proportion of the erroneous bits read out before the use of the error-correction codes.

The idea of holographic data storage has existed since the discovery of holography. Recent development of opto-electronic devices and storage materials gives a new impetus for the research and development in this field. The increasing level of research and development in this field induces a growing demand for the development of models that describes accurately the system and the storage materials. Usually the point spread functions (PSF) of the optical systems form the basis of the modeling. Since these models determine the convolution of the brightness of pixels and the PSF, they are generally called convolution models. The existing models are limited by dealing only with special aspects of the systems or describing only parts of the systems and by taking into account the interaction of a low number of neighboring pixels.

Objectives

My work aimed to develop a general, usable, and accurate model that takes into account the interaction between the pixels of the page-organized data as well as the relations between the system and the storage material. Such a model can open new research areas. I wished to create a model that is based on the complete image of the optical wave front, and deals with the holographic data storage as a complex, integral system. There are no models with these characteristics in the literature. Since this type of modeling requires Fast Fourier Transform, the model falls into the category of the FFT models.

The practical aim of the work included the realization in a simulation software and its application for the analysis, testing, correction, optimization, development and design of holographic data storage systems. I employed my results in the R&D of the Holographic Memory Card (HMC) system that was a joint work of the Budapest University of Technology and Economics and the Optilink Ltd.

In my dissertation I outlined my research work establishing the model and its realization. I also wrote about the study of the storage material, the mathematical description of its properties and the incorporation of these results into the model. I gave an account on my results in the design and optimization of holographic system. I summarize the main results in four thesis points as follows.

New Scientific Results

1. I established a general model of the Fourier-type holographic data storage systems that surpasses the ones described in the literature in several respects, as follows: The model takes into account the interaction between the pixels of the page-organized data; describes the entire system by including submodels for the optical and optoelectronic components. I showed that the combined effect of the various physical phenomena in the system can not be described by modeling the physical processes separately due to the complexity of the system and to various non-linear effects. I found out that the individual analysis of pixels or group of pixels, that form the basis of the existing models, is not sufficient. I established the processing of entire images in the model. Based on the modeling work described above and a known FFT algorithm I developed a simulation software. Using this software I carried out simulation studies and compared the results with the actual experiments. I found that the model describes well the behavior of the systems based on Fourier-type holographic data storage and can be used for their analysis, optimization and design. [1, 2, 3]

2. Within the frame of this model, I worked out a description for the dynamic behavior of the storage material, allowing precise modeling of the saturation and the nonlinear responses of the storage material. I verified the operation of the description by comparing simulations and experiments in holographic data storage environment. Using the model, I studied the dynamic behavior of azobenzene polyesters that are widely used in holographic data storage. I found that the properties of the system, like the bit-error rate and the diffraction efficiency, are determined mainly by the saturation of this material. This effect has not been recognized earlier in the literature. [4, 5]

16 E. Lőrincz, G. Szarvas, P. Koppa, F. Ujhelyi, G. Erdei, Sz. Mike, A. Sütő, P. Várhegyi, Sz. Sajti, Á. Kerekes, P.S. Ramanujam, "Different solutions of high density holographic data storage", invited talk at Kick Off Meeting of the COST Action P8, "Materials and Systems for Optical Data Storage and Processing", Berlin, June 24-25 2002

17 E. Lőrincz, G. Szarvas, P. Koppa, F. Ujhelyi, G. Erdei, A. Sütő, P. Várhegyi, Sz. Sajti, Á. Kerekes, T. Ujvári, P. S. Ramanujam, "Polarization holographic data storage using azobenzene polyester as storage material", invited paper at Photonic West, Conference 4991 Organic Photonic Materials and DevicesVI, Optoelectronics 2003, 25-31 January 2003. San Jose, California, USA, published in Proc. of SPIE 4991 Organic Photonic Materials and Devices VI., J. G. Grote, T. Kaino editors, pp. 34-44.

18 P. Koppa, G. Szarvas, F. Ujhelyi, G. Erdei, A. Sütő, P. Várhegyi, T. Ujvári, Sz. Sajti, P. S. Ramanujam, E. Lőrincz, "Holographic data storage with organic polymer films", invited paper at SPIE Annual Meeting, 3–8 August 2003, San Diego, California, USA, Conference AM436, Proc. of SPIE 5216, Organic Holographic Materials and Applications, ed. Klaus Meerholz, pp. 165-177.

19 P. Koppa, P. Várhegyi, T. Ujvári, M. Lovász, G. Szarvas, F. Ujhelyi, G. Erdei, J. Reményi, Domján, A. Sütő, E. Lőrincz, "Application of polarization holography for data storage", COST P8 Workshop in Paris, 16-17 September, 2004

20 T. Ujvári, P. Koppa, M. Lovász, P. Várhegyi, Sz. Sajti, E. Lőrincz, P. Richter, "Secure data storage system based on phase-encoded thin polarization holograms", J. Opt. A: Pure Appl. Opt. 6, pp. 401-411, 2004

21 M. Lovász, T. Ujvári, P. Várhegyi, A. Sütő, P. Koppa, "Security application of polarization holography", COST P8 Workshop in Paris, 16-17 September, 2004

Further Scientific Publications

11 P. Koppa, G. Erdei, F. Ujhelyi, P. Várhegyi, T. Ujvári, E. Lőrincz, G. Szarvas, S. Hvilsted, P. S. Ramanujam and P. Richter, “Data storage on holographic memory card”, in Holography 2000, Tung H. Jeong, Werner K. Sobotka, Editors, Proc. of SPIE Vol. 4149, pp. 309-314, 2000

12 E. Lőrincz, F. Ujhelyi, P. Koppa, A. Kerekes, G. Szarvas, G. Erdei, J. Fodor, Sz. Mike, A. Sütő, P. Várhegyi, P.S. Ramanujam, S. Hvilsted , "Read/write demonstrator of rewritable holographic memory card system", in Optical Data Storage 2001, Terril Hurst, Seiji Kobayashi, Editors, Proc. of SPIE Vol. 4342, pp. 566-573, 2001

13 E. Lőrincz, F. Ujhelyi, G. Szarvas, P. Koppa, G. Erdei, F. Józsua, Sz. Mike, A. Sütő, P. Várhegyi, P. S. Ramanujam, S. Hvilsted, P. I. Richter: ”Polarization holographic data storage system”, invited lecture at the Fourth Annual Meeting of the COST Action P2, Budapest, 16-19 May 2001

14 Á. Kerekes, E. Lőrincz, Sz. Sajti, P. Várhegyi, P. S. Ramanujam, S. Hvilsted, ”Dynamic behavior of azobenzene polyester used for holographic data storage”, in Applications of Ferromagnetic and Optical Materials, Storage and Magnetoelectronics, Matthias Wuttig, Lambertus Hesselink, Herman J. Borg, Editors, MRS Proceedings Volume 674, V3.4, MRS Spring 2001

15 G. Szarvas, P. Koppa, A. Sütő, P. Várhegyi, Sz. Mike, G. Erdei, F. Ujhelyi, L. Gazdag, E. Lőrincz, "Multilayer Thin-film Holographic Storage - a New Approach", Technical Digest of ISOM / ODS 2002, Joint International Symposium on Optical Memory and Optical Data Storage 2002, 7-11 July 2002, Hawai, pp. 240-242, IEEE Catalog No. 02EX552, 2002

3. I showed that the reliability, capacity and speed of the HMC system can be optimized by simulation studies, using the model developed. The parameters found to influence the performance of the system were the reference beam profile; the geometry of the hologram; the distance of the neighboring holograms; the number of gray scale levels during the display of the data; the fill factor and contrast of the spatial light modulator; and the dynamical range of the detector. Based on the optimization by the model, I suggested a new combination of the above listed parameters that resulted in higher data density and writing speed at lower bit error rate. This general optimization method can be employed for other holographic data storage systems too. [1, 6, 7, 8]

4. I created a new phase mask, the 4-level phase mask with random base points and limited phase steps that can effectively smooth the intensity peaks arising in the hologram plane. I carried out a comparative analysis of the various methods for smoothing the intensity of the Fourier plane (phase masks, axicon, and defocusing) and found that my new phase mask is optimal for smoothing the high intensity peaks as well as improving the bit error rate and the writing speed. The performance of this tool proves that the FFT-based model is suitable for the design, analysis and iterative optimization of new system elements. Experiments carried out with the presently used 2-level phase mask of the HMC system support my simulation results. [4, 6, 9, 10]

Utilization of the Results

The model was realized in a simulation software package that is a user-friendly tool with easy operation and transparent functioning. This software is suitable to the analysis and multiparametric optimization of most page-organized holographic systems. Every parameter can be examined and optimized alone or in combination with other parameters. My colleagues have successfully employed this software in their R&D activities. Those results that are listed in section “Further Scientific Publications” could not be achieved without this model and software. Besides, the optimal parameters that I determined were used in the design and developing of the HCM system.

Scientific Publications Related to the Thesis Points

1 P. Várhegyi, P. Koppa, E. Lőrincz: „System modeling and optimization of Fourier holographic memory”, Applied Optics, in press 2005

2 P. Várhegyi, P. Koppa: „Polarizációs Fourier holográfia modellezése és szimulációja”, V. Szimpózium „A Hazai Kvantumelektronikai Kutatások Eredményeiről” 2003

3 T. Ujvári, P. Várhegyi, P. Koppa, G. Szarvas, E. Lőrincz, F. Ujhelyi, Á. Kerekes, L. Domján, P. Kalló, P. Richter: "Holografikus adattárolás", Magyar Optik konferencia, 2000

4 P. Várhegyi, Á. Kerekes, Sz. Sajti, F. Ujhelyi, P. Koppa, G. Szarvas, E. Lőrincz, "Saturation effect in azobenzene polymers used for polarization holography", Applied Physics B, Vol. 76 No. 4 pp. 397-402 2003

5 P. Várhegyi, Á. Kerekes, Sz. Sajti, P. Koppa, E. Lőrincz, G. Szarvas, P.S. Ramanujam, S. Hvilsted and P. Richter: "Nonlinear saturation effect in azobenzene polymers used for polarization holography; experiments and theoretical modeling", COST P2, Budapest, Hungary, 16-19 May 2001

6 P. Várhegyi, P. Koppa, E. Lőrincz, G. Szarvas and P. Richter, "System modeling and optimization of the polarization Fourier holographic memory card", ICO 19 International Conference on Optics, Firenze, Italy, 25-30 August 2002

7 P. Várhegyi, P. Koppa, E. Lőrincz, G. Szarvas, and P. Richter, „Optimization of the storage density in thin polarization holograms”, Holography 2000, 10-14 July 2000, St. Pölten, Austria, Tung H. Jeong, Werner K. Sobotka, Editors, Proc. of SPIE Vol. 4149, 2000

8 P. Koppa, P. Várhegyi, T. Ujvári, G. Szarvas, S. Hvilsted, P. S. Ramanujam, P. Richter, ”Storage density enhancement in holographic memory card system”, Nonlinear Optics for the Information Society, ed. Alfred Driessen, pp. 179-184, ISBN 1-4020-0132-0, Kluwer Academic Publisher, 2001

9 J. Reményi, P. Várhegyi, L. Domján, P. Koppa, E. Lőrincz, "Amplitude, phase and hybrid ternary modulation modes of a twisted-nematic liquid-crystal display at ~400 nm", Appl. Optics, Vol. 42, No. 17, pp. 3428-3434, 2003

10 G. Erdei, G. Szarvas, E. Lőrincz, J. Fodor, F. Ujhelyi, P. Koppa, P. Várhegyi, P. Richter, “Optical system of Holographic Memory Card writing/reading equipment”, Proc. SPIE, Vol. 4092, pp. 109-118, Novel Optical System Design and Optimization III, Ed. Jose M. Sasian, 2000