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MICRO- AND NANO-FOCUSING OPTICS INTENDED FOR REMOTE IMAGING SYSTEMS

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Abstract

Some possible remote and aerospace applications of nano-focusing optics are discussed. Optical systems for micro-focusing built by aberration corrected lens modules are presented. Components for nano-focusing in the read/write CD/DVD heads are given also. Diffraction limited spots having diameters from 400 nm to 200 nm are analyzed. Near-field optical technologies for the concentration of laser energy in spots from 200 nm to 100 nm are used in the designed nano-focusing modules intended for the tera-byte drives. Techniques for conversion various laser beams of light through hybrid lenses in which an aspherical refractive surface corrects the longitudinal spherical aberrations are reported. The diffractive surface introduces a negative dispersion and removes the chromatic aberrations in the image plane. Examples of wave-optics nano-focusing numerical modelling fulfilled by Finite Difference Time Domain method are presented. Video-spectrometers and remote imaging systems are analysed as platforms for tera-byte memories.

1. Introduction

Remote imaging systems are applied for spectral analysis of the Earth’s surface [1 - 4]. The optical devices “Spectrum-15” and “Spectrum-256” have been used by Bulgarian spacemen G. Ivanov and A. Alexandrov. These aerospace instruments are intended for remote spectrometry of the Earth and realized at the Bulgarian Academy of Sciences under the supervision of acad. Dimitar Mishev [1, 3, 4]. The innovative tera-byte optical memories are potential candidates for the recording of million pictures generated by video-spectrometers. A great volume of spectrometric data is transmitted from the aerospace crafts to the analyzing centers [1, 4]. Advanced optical devices have the potential to satisfy the ever-increasing storage demands of computer systems, both in terms of high-capacity and massive transfer rates [5 - 7]. Novel technologies are at various stages of development and promise to provide the next generation of optical storage systems. High-density optical disk memories will require accurate characterization and very precise measurement of the dominant error sources in each micro-technology [7 - 9].

Nano-focusing is determined as light collecting into a spot size diameter under 200 *nm*. The conventional micro-lens systems can focus laser beams into spots from 1 *μm* to 0.4 *μm*. Nano-focussing research is a part of the field of nano-photonics directed to nanoscale light-matter interaction and nano-fabrication of optics. The production accuracy of the existing optical technology is from 1/10 wavelength to $\lambda/20$ that is about 60 – 30 *nm* during the precise micro-lens surface diagnostics.

A huge growth of nano-photonics production can be noted during the first decade of new century in four major directions: materials, biomedicine, molecular electronics, and energy (nano-devices: solar & fuel cells). This tendency was kept also during the next ten years. For example: the governments spent more than $4 billions on NANO-Tech research in 2004; the EU government funding for nanotechnology was about 1.3 billion Euro from 2002 to 2006; in 2009 the world white market of nano-photonic devices showed a growth rate of 85.8% reaching about $ 9.33 billions.

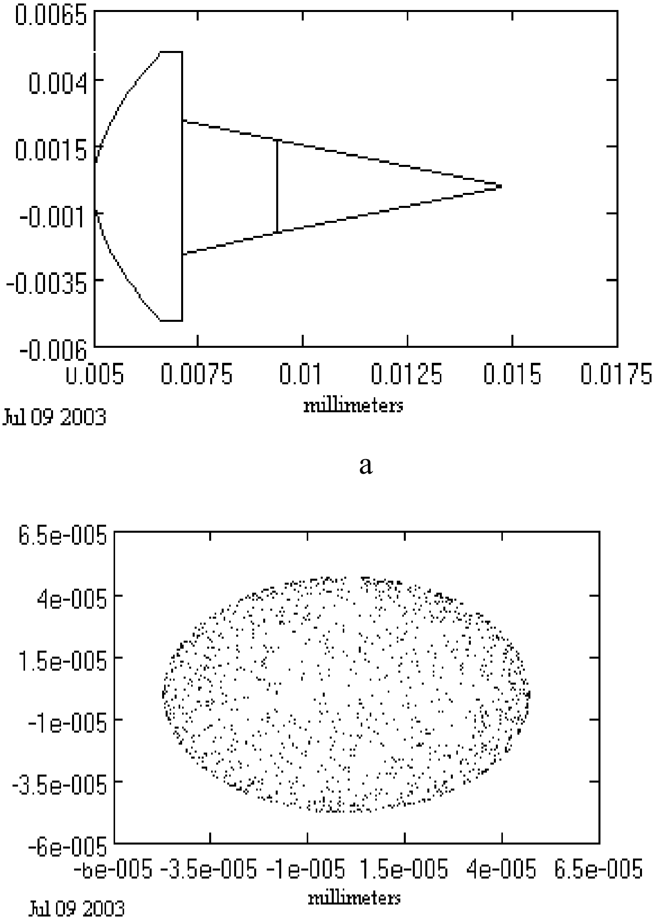
The micro-lenses are essential elements of the modern optical-electronic devices. They can be found in aerospace industry, optical communications, interconnections, sensors and displays, charge-coupled device (CCD) cameras. Micro-lenses arrays are key components in modern optical disk memory heads also [5 - 7]. The development of a new ultrahigh-density optical disk head system using a vertical cavity surface emitting lasers (VCSEL) array as a parallel optical beam source, to realize a higher memory density and a fast data transfer rate is in a process of completion at the Terra-byte Laboratory of Tokai University, Japan. It will work at near-field optical conditions, in which the gap between the head output surface and the optical disk surface have to be as narrow as 10 *nm*. A GaP micro-lens array, aligned to the VCSEL-s should concentrate the light at 30 *nm* in diameter apertures opened at micro-lens focus spots in an Au film, deposited on the head output surface with nano-thickness. The modeling, design and fabrication of refractive micro-lens arrays and their integration with VCSEL arrays was accomplished successfully recently. Using the finite difference time domain (FDTD) method a design of a gallium phosphide (GaP) micro-lens array (MLA) optically integrated with a microprobe array has been fulfilled. The measured full width half maximum (FWHM) spot size is only 520 *nm* after the fabrication of the GaP MLA [10]. The MLA design and fabrication used in a near-field parallel optical head is also demonstrated.

Some aspects related to the design of a nano-focusing probe intended for a near-field optical head are presented in this report.

2. Design of Micro-lenses for Ultra-high Density Optical Storage

The main ultra-high density optical storage (UHDOS) requirement is to design free of aberrations nano-focusing recording modules applied in arrayed memory heads and to fabricate nano-photonics integrated structures. We discuss the design characteristics and further methods for amendments the optical performance of the nano-focusing probe realized for a UHDOS system. Some results derived in the development process of nano-focusing probe optimization applying anti-reflection coatings (ARCs) are reported. The balancing of the residual aberrations and technological errors is also evaluated for the developed near-field optical head. This research focuses on the nano-probe configurations with the possible aberration solutions, the recording specifications and theoretical background of the problem, the micro lens (ML) shape and calculation formulae, the ray and wave front analysis, the nano-spots energy distribution and optical power density computing using FDTD numerical method [11].

A preliminary ray-trace analysis of the micrometer-scale lens structure is carried out using the “Interactive Ray Tracing” software [7]. An optical focusing configuration for a spherical surface having a diameter of 10 *μm* and focal length of 10 *μm* is given in Fig.1a. A computing of 3500 nano-focused rays with the aid of this micro-lens to a spot size under 85 *nm* is shown in Fig. 1b.



a

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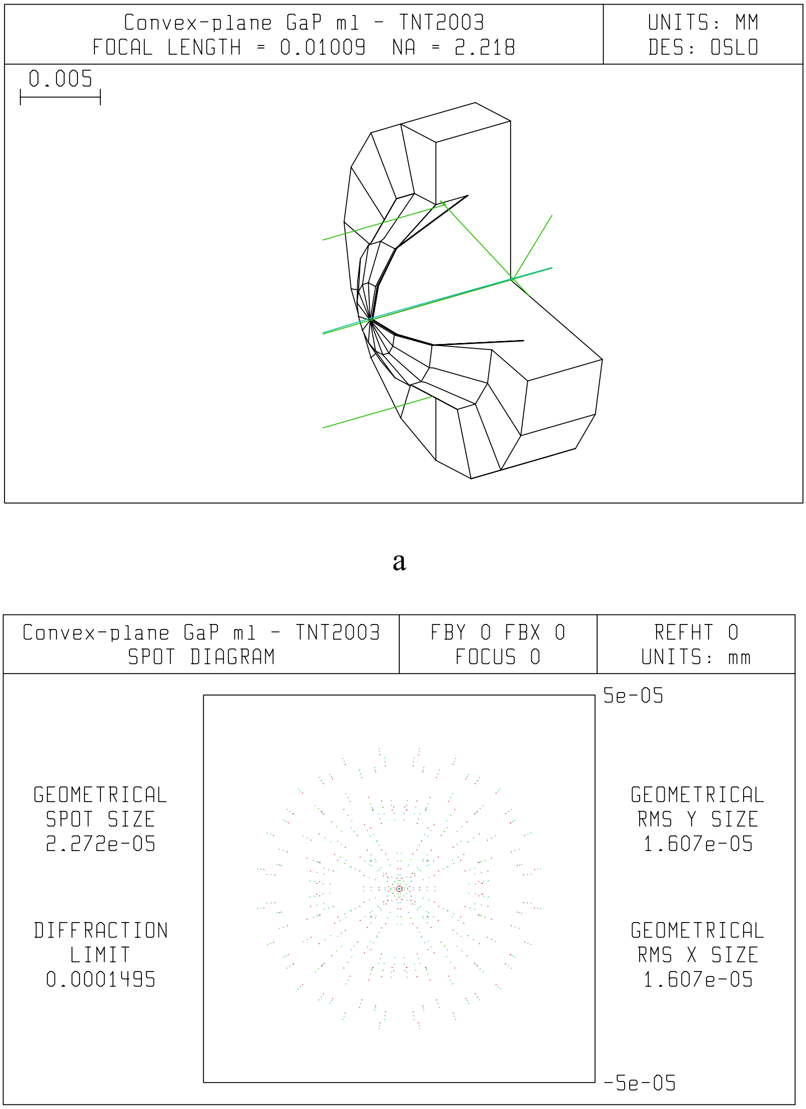
Fig. 1. Preliminary ray-trace analysis for a spherical micro-lens

The only ML refractive surface (Fig. 2) focuses a VCSEL beam on the ML rear plane surface. The ML module must be corrected for transversal aberrations on the exit flat GaP surface. The axially symmetric optical surface can be fabricated as spherical or aspherical [7]. The exact ML surface is ellipsoidal for this developed near-field optical head. The nano-aspherization of the ML convex surface is fulfilled using reactive ion etching (RIE) technology during the super-polishing process [7, 12]. The maximal nano-polishing value is about 150 *nm* on the periphery area of the ML surface having a diameter of 13 *μm* (Fig. 2a).



a

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Fig. 2. Micro-lens with aspherical frontal surface

High numerical aperture (NA) convex-plane ML module is designed also using the Optical Software for Layout and Optimization (OSLO). The obtained ML component having NA = 2.17 with anti-reflection coatings (ARCs) is presented in Fig. 3a and the point spread function on the rear ML plane surface with deposited ARCs is given in Fig.3b.

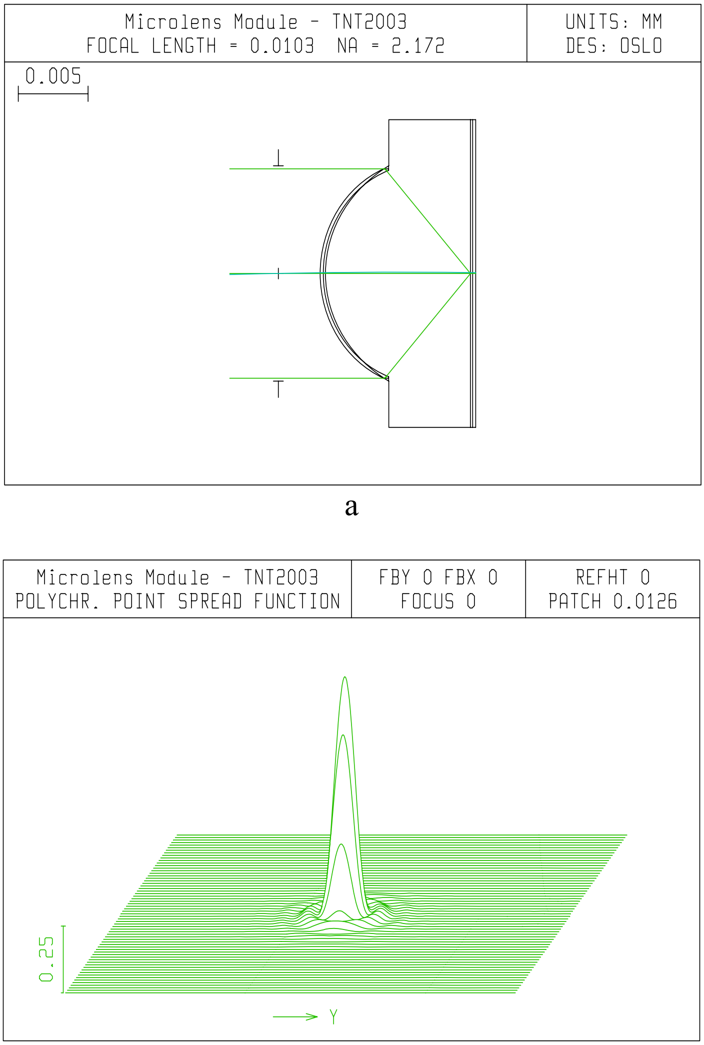

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Fig. 3. High numerical aperture (NA) convex-plane micro-lens (ML) module

3. Wave-optics Nanofocusing Numerical Modelling

Finite Difference Time Domain (FDTD) Method [11] is used for 3-D simulation of electromagnetic field (light) propagation of in a non-magnetic environment using. The derivatives in the time are expressed by finite difference approximations. The Maxwell's equations in this case are:

(1) $$\nabla \times E(r,t) = -\mu \frac{\partial H(r,t)}{\partial t}, \; \nabla \times H(r,t) = \sigma E(r,t) + \varepsilon \frac{\partial E(r,t)}{\partial t},$$

where E is electric fields, H is magnetic fields, ε is electric susceptibility of the medium, μ is magnetic permeability of the medium and σ is media conductivity.

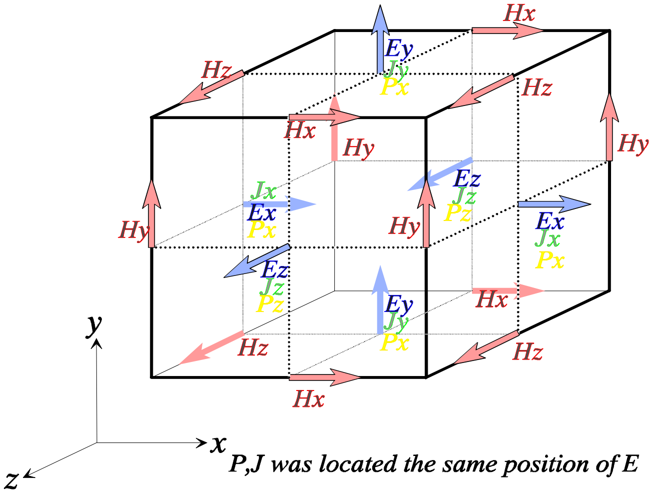
The temporal derivatives in these equations are written using finite difference approximations:

(2) $$E^n = \frac{1-\frac{\sigma\Delta t}{2\varepsilon}}{1+\frac{\sigma\Delta t}{2\varepsilon}} E^{n-1} + \frac{\frac{\Delta t}{\varepsilon}}{1+\frac{\sigma\Delta t}{2\varepsilon}} \nabla \times H^{n-\frac{1}{2}},$$

(3) $$H^{n+\frac{1}{2}} = H^{n-\frac{1}{2}} + \frac{\Delta t}{\mu} \nabla \times E^n,$$

where *Δt* is step in time and *n* is index of the respective step.

The spatial derivatives *∇×E(r,t)* and *∇×H(r,t)* are written by their components and are also presented using central finite difference approximation (Fig. 4).



P,J was located the same position of E

Fig. 4. 3-D spatial coordinates location in the vector cube

A pseudo color 2-D picture of the light propagation at a GaP wafer after a ML, made by the same optical material without surface NANO-focusing optimization, derived numerically by FDTD method is shown in Fig. 5. The focused spot diameter is about 250 *nm*.

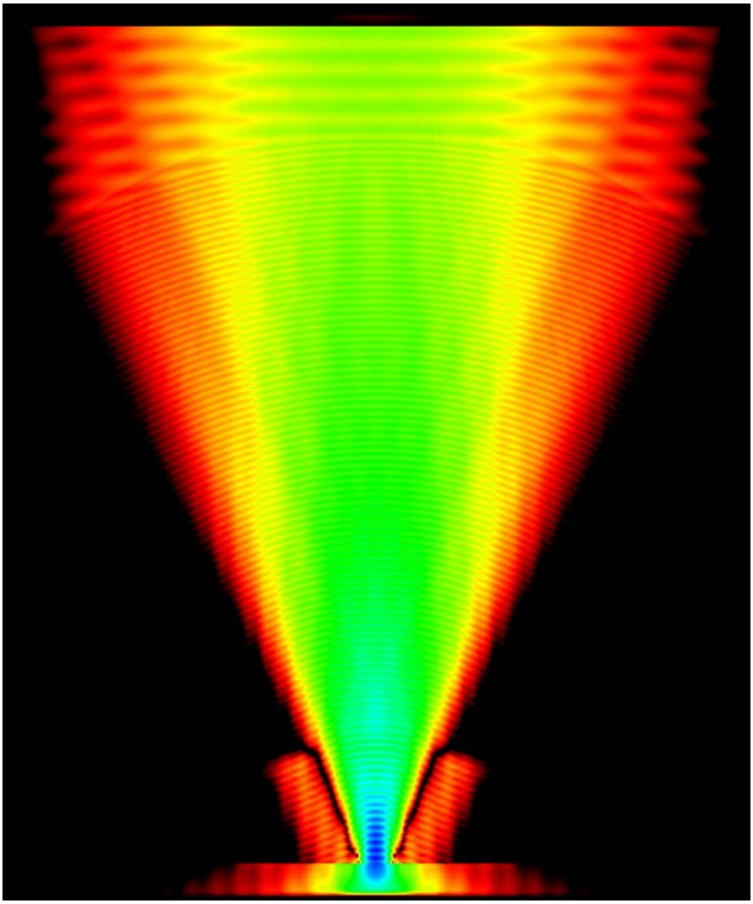


Fig. 5. 2-D FDTD NANO-spot of about 250 nm

An optimized 3-D structure of the GaP micro-lens with anti reflection coating, and the lens diffraction knife-edge function with a full width at half maximum (FWHM) size of 130 *nm*, obtained by OSLO program, are plotted in Fig. 6.

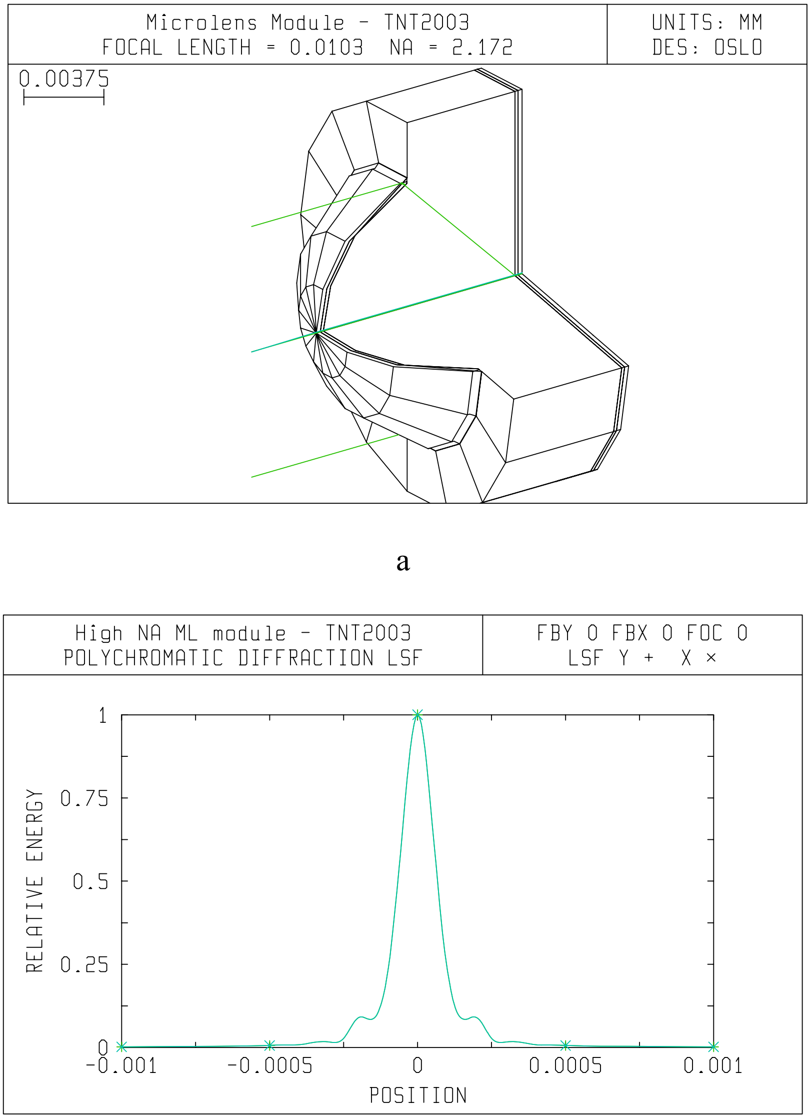


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Fig. 6. Nano-focusing module optical design

The FDTD method 2-D pseudo color picture of the light propagation of this lens is presented in Fig. 7. Its optical power density is focused to a spot of 200 *nm*.

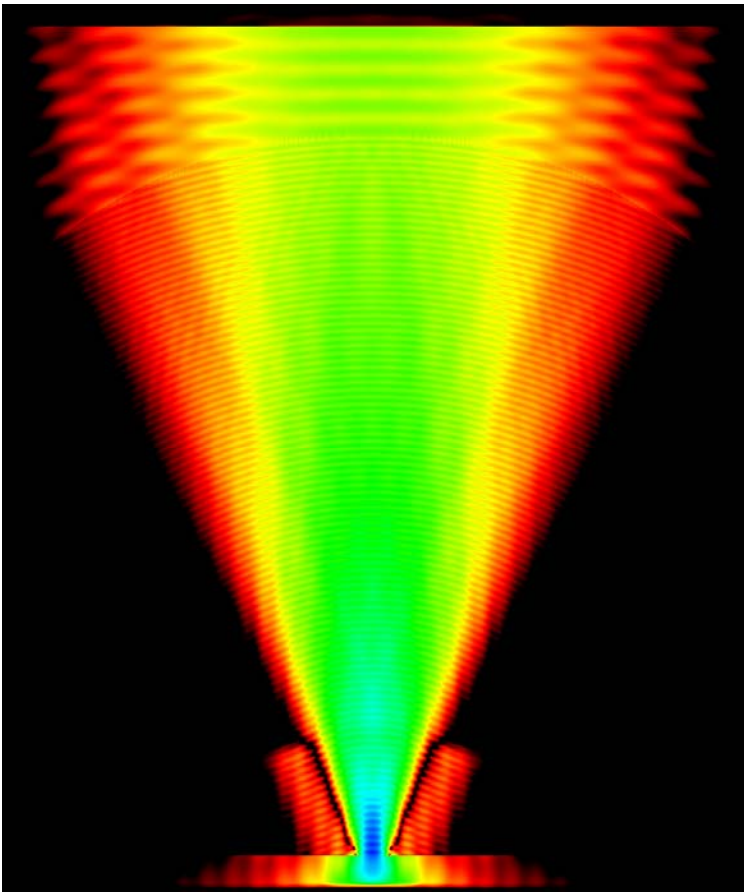

Fig. 7. 2-D FDTD nano-spot of about 200 nm

It is seen from the reported results that the optimization of nano-focusing system UHDOS by means of optical design software allows reaching the spot of the focused light energy with a minimum diameter of 200 *nm*. But in order to achieve recording terra byte densities on a standard optical disk with a diameter of 120 mm, the laser beam spot radius should be about 30 *nm*. Another physical principle is used in addition to satisfy this requirement. A computational domain structure is defined for FDTD-simulation, according to which a collimated light beam with wavelength λ = 780 *nm*, propagating through a CaP wafer, is directed along a nano structured Au layer, deposed on the wafer surface. An aaperture with diameter of 30 *nm* was made in the central part of this film (Fig. 8a).

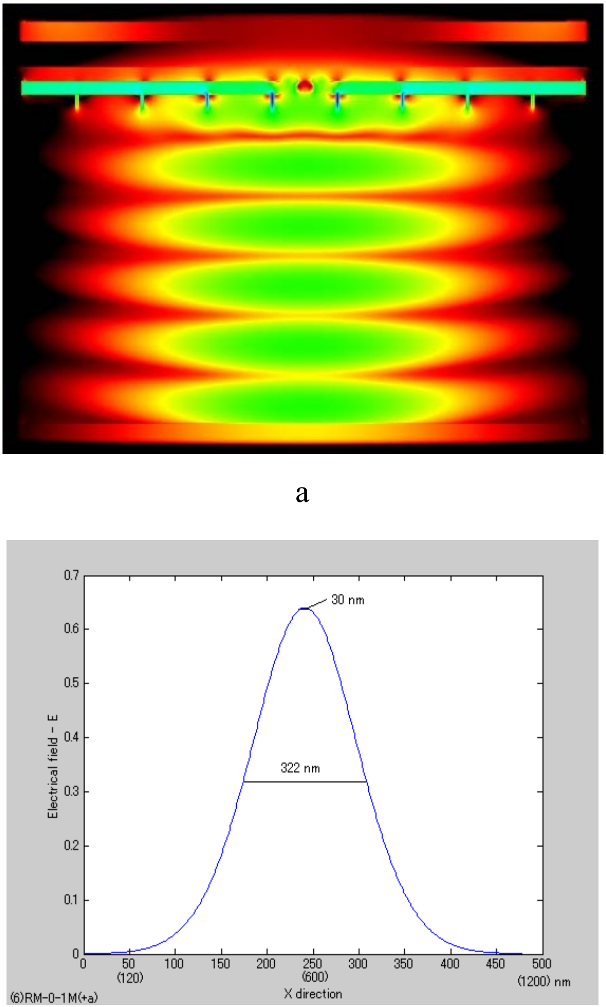

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Fig. 8. The 2-D electric field intensity distribution of in recording media plane

During the FDTD simulations the thickness of the gold coating, the distance between the teeth of the grating thickness or height have been varied, keeping fixed the nano-aperture diameter - 30 *nm*, the thickness of the air layer between the recording medium and Au layer - 20 *nm*, and the recording medium thickness - 20 *nm*. Configuration and dimensions of the nano-structure gold coating at which the laser light spot of 30 *nm* over the recording medium surface was obtained, delivering energy sufficient enough to realize its phase transition (Fig. 8b).

4.Conclusion

The ultra-high density near-field optical memories are under research and development (R&D), because a number of computer modules having tera-byte capacities can be fabricated at present [5 - 9, 13, 14]. The fabricated micro-lens is one of the basic elements of such memory. It is covered by ARC system of SiO_2/Si_3N_4 type applied to the fabricated micro-lens as a hard protective structure [8, 9, 13]. After the nano-polishing process the GaP micro-lens array's plane surface is coated with a thin Si_3N_4 protective layer. The optical sensitive IR film is sputtered over the Si_3N_4 layer for the next nano-recording procedure. The obtained nano-focusing probe has an enlarged NA of 2.153 (Fig. 6). This NA value is about three times larger than the previous published result [5]. The optimized arrayed probe possesses nano-focusing energy efficiency about 43 times higher than the values published in the reports of the previous papers [8]. The computed nano-focused spots diameters are from 20 *nm* at the geometrical micro-lens limit, up to 130 *nm* at the diffraction FWHM size applying ARC systems (Fig. 3 and Fig. 6). The realized nano-focusing probe is an aberration-free optical system computed for geometrical spots and optimized for wave-front spread functions and FDTD spot sizes [9, 13].

Using an optimization with two-layer and one-layer anti-reflection coatings (ARC) one can obtain an energy throughput from 4.0 to 4.75 times higher than the output of the micro-lens without ARC [8]. The FDTD calculated spot size is limited to 200 *nm* for a micro-lens radius of 6 μm (Fig. 7). This spot is near to the diffraction limit of 150 *nm* computed for the same ARC optimization design of the nano-focusing probe. An additional advantage of the ARC process is that it can fabricate multilayer nano-films having a good quality.

Additional application of gold nano-structured thin coating on the recording probe output surface allows further concentration of the light energy delivered through the optical focusing system in a nano-sized spot necessary to achieve terra-byte optical recording density and energy - quite sufficient for inducing a phase transition of the recording medium through available power of the VCSEL radiation. This option applied in combination with the produced micro-lens focusing system, provides a good potential for optimal design and implementation of a write/read head for the ultra-high density optical storage.

Video frames consist of an average volume about 10^5-10^6 bits which reflects the visual speed of 0.1 - 0.05 s for the receiving simultaneous images. The retina compresses visual information from 10^{12} bits to 10^6 bits and the brain detects luminance and geometrical features of the observing objects [3, 4]. The video spectrometer generates hyperspectral cubes having from 300 to 900 monochrome pictures with capacity up to 10^9 bits for every one Earth's strip [15, 16]. The remote camera records up to 60-100 thousand color images during one circle over the Earth requiring a tera-byte optical memory with information capacity of 10^{12} bytes. Our research efforts continue with the lab-grade fabrication of experimental near-field parallel nano-focusing heads applied in the high-density disk memories. The innovative aerospace optical systems are under R&D intended for the generation and remote transmission of million color and spectral-zonal images of the Earth's surface. This volumetric remote data can be stored using parallel tera-byte optical memories.

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МИКРО- И НАНО-ФОКУСИРАЩА ОПТИКА, ПРЕДНАЗНАЧЕНА ЗА ДИСТАНЦИОННИ ИЗОБРАЗЯВАЩИ СИСТЕМИ

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Резюме

Обсъдени са възможни приложения на нано-фокусираща оптика при авиокосмически дистанционен мониторинг. Представени са оптични системи за микро-фокусиране, съставени от модули, съдържащи лещи с коригирани аберации, както и оптични системи за нано-фокусиране при оптични CD/DVD глави за четене и запис на информация с терабайтова плътност. Анализирани са дифракционно ограничени фокусни петна с диаметри от 400 *nm* до 200 *nm*. За създаване на оптичните запаметяващи устройства с терабайтова плътност на записа са използвани технологии за концентриране на лазерната енергия в петна с размери от 200 *nm* до 30 *nm*, основани на оптиката на близкото поле. Докладвани са техники за преобразуване на различни лазерни снопове светлината чрез хибридни лещи, в които асферична пречупваща повърхност коригира надлъжните сферични аберации. Дифракционната повърхност въвежда отрицателна дисперсия и премахва хроматичните аберации в равнината на изображението. Представени са примери за числено моделиране на нанофокусиране в пространството на вълновата оптика изпълнен чрез метода на крайните разлики, развит във времето. Визирани са видеоспектрометри и системи за дистанционен мониторинг чрез системи за запис и обработка на изображения като платформи за оптична памет с терабайтова плътност.