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Technologies of Laser Radiation Focusators

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Abstract: The study analyzes a wide range of technologies generated by the creation and application of focusators of laser radiation. I give a brief review of methods for solving ill-posed inverse problems of diffraction theory, the methods of monitoring and substrate forming a diffraction micro-relief, optical systems and devices for experimental research of focusators, laser technologies and units on their basis.

Key words: Focusators of laser radiation, computational experiment, diffractive optical elements, formation of diffractive microrelief, laser technologies

INTRODUCTION

Functioning of Diffractive Optical Elements (DOE) is based on diffraction of monochromatic light on a microrelief. Due to adjustability of computer-aided design of diffractive microrelief and modern precision equipment capacity for its formation, we have a unique optical tool necessary for required focusing of laser radiation (Golub *et al*., 1981, 1991a, 1992a).

In the course of years passed since the first publication (Golub *et al*., 1981) of a revolutionary idea of Prokhorov, Sisakyan, Soifer of a possibility to use diffractive microrelief to achieve a required focusing of laser radiation into a specified area, people developed a wide range of technologies, connected with making and usage of laser radiation focusators.

Possibility to concentrate radiation on a fragment of a surface of a required shape allows to create new technologies and means of their implementation, providing different products with new performance properties. Diffractive optical elements are used in medicine, machine tool building, in optical systems in tooling, food and pharmaceutical industries in lighting engineering in the agricultural sector and also they can be essential for many other types of human activities.

In this research, researchers analyzed the influence of focusators creation on development of diffraction optics, optical instrument making and mechanical-engineering technologies.

FOCUSATORS DESIGN APPROACH

To design a focusator diffractive microrelief we need to solve an inverse problem of diffraction theory regarding this optical element's phase function. Because of complexity of the inverse problem it is usually solved in the frame of geometrical optics approximation (Golub *et al*., 1981, 1991a, b, 1992b; Born and Wolf, 1968; Serafimovich, 2014; Doskolovich *et al*., 2002, 1995a, b, 1993; Kazanskii, 1989; Kazanskiy *et al*., 1995; Kazanskiy and Soifer, 1994). Due to ill-posedness of diffraction theory inverse problems in some cases we can see several types of a projected focusator phase function. For example, during focusing into a longitudinal segment (Golub *et al*., 1981, 1988a; Kazanskii, 1989; Doskolovich *et al*., 1995a), focusing of a round beam into a rectangular domain (Doskolovich *et al*., 1993) and so on. Revealing the most effective solution is especially important for basic (the most widespread) problems of focusing. For instance, solving of problems of focusing into a transverse segment (Kazanskiy and Soifer, 1994; Doskolovich *et al*., 1995b; Soifer *et al*., 1998) and a ring (Golub *et al*., 1988a; Soifer, 2013) is basic for focusators directed at letters (Khonina *et al*., 2011a; Golub *et al*., 1991c) and solving of problems of focusing into a rectangle is basic for design of focusators for planar domains (Soifer *et al*., 1995; Doskolovich *et al*., 1996). It is interesting that solutions obtained for laser radiation focusing appeared to be useful for focusing of surface electromagnetic waves (Bezus *et al*., 2010, 2011a, b, 2014).

In some cases (for example, complex forms of distribution of intensity or focal region) it is impossible to obtain an analytic expression for the focusator's phase function. In these cases, we apply different iterative methods of solving of inverse problems at approximation of the scalar theory of diffraction (Kazanskii, 1989; Kazanskiy *et al*., 1994). Developed design methods are combined in corresponding software products (Kazanskiy *et al*., 1994; Golovashkin *et al*., 2002; Volotovskii *et al*., 2001; Doskolovich *et al*., 1995c; Kazanskiy, 2006, 2012).

To find the best solution, we need to analyze focusators' output parameters (Serafimovich, 2014; Golub *et al*., 1988a; Doskolovich *et al*., 2002). Among characteristics describing processes of creation and functioning of focusators we can mark out three types of parameters (Serafimovich, 2014; Golub *et al*., 1988a; Doskolovich *et al*., 2002). The first type includes physical parameters taken as a basis of DOE phase function estimation: focal distance; wave operating length; size of a focusator and a focusing domain and also characteristics describing its shape and a shape of a focused beam; angle of radiation's incidence onto an optical element etc.

The second type includes parameters of discretization and quantization of a focusator's phase function, size and shape of elements of the focusator microrelief spatial resolution. These parameters are connected with choice of a registrator of DOE phase function and specificity of its estimation.

The third type includes focusator's diffractive properties-energy efficiency width of a focal line, root-mean-square deviation of an obtained distribution of intensity in a focal region in comparison with a required one and so on.

For design of focusing DOE the first two types of parameters are internal and diffractive parameters are external, resulting from functioning of a focusator with chosen internal parameters. For research of a focusator it is important to reveal the connection between external and internal parameters of design. Moreover, considering labour required for and multivariance of DOE creation procedure, focusator's characteristics should be studied as early as at the design stage. For such analysis asymptotic methods of research of focusing DOE phase function, information technologies and software tools of computational experiment were developed (Serafimovich, 2014; Golub *et al*., 1988a; Doskolovich *et al*., 2002).

ANALYTICAL ASYMPTOTIC METHODS OF RESEARCH

At the initial stage of creation of a new focusator it is important to carry out an analytical diffractive estimation of the focused radiation taking into account finite size and DOE's concrete physical parameters (Golub *et al*., 1987; Golub *et al*., 1992, 1989a; Kazanskiy *et al*., 2000a; Kazanskiy *et al*., 1996; Kazanskiy and Kharitonov, 2012; Kazansky, 1990). The analysis of obtained diffractive correlations allows to study limitations of the geometrical optical approach taken as a basis for estimation of the focusator's phase function to reveal initial values of physical parameters which lead to destruction of a required shape of a domain of focusing to find possible mistakes in the diffraction theory inverse problem analytical solution. However, analytical research can be carried out only for the simplest phase functions, lighting beams and domains of focusing such as ring (Golub *et al*., 1991, 1987; Soifer, 2013) set of points, longitudinal (Golub *et al*., 1988a, 1989a; Serafimovich, 2014; Kazanskiy *et al*., 2000a) and transverse (Kazanskiy *et al*., 1996; Kazanskiy and Kharitonov, 2012) segments.

In some cases as a result of analytical research one can obtain diffractive corrections to the focusator's phase function. Nevertheless within a framework of an analytical research it is impossible to take account of discretization and quantization of the focusator's phase function which emerge during DOE creation.

COMPUTATIONAL EXPERIMENT

Methodology and software tools of the computational experiment were developed for further and more comprehensive researches of focusing DOE (Golub *et al*., 1988a; Kazansky, 1990; Doskolovich *et al*., 1995d); these methodology and tools allow to account impact of discretization and quantization of a focusator's phase function which emerge during designing and making of DOE.

The same problem arises when focusing problem solution is obtained with the help of different numerical approaches and it is necessary to study obtained solutions thoroughly. The choice of the best solution for concrete internal (first of all physical) parameters of the problem must be done on the basis of computational experiment data (Serafimovich, 2014; Golub *et al*., 1988a).

The most important line of this research is estimation of energy deposition applied to process material in relation to the focusator's technological role marking, hardening, formation of nanopores and so on.

Presence of a wide range of different methods of focusators diffractive microrelief formation (Popov, 1989; Volkov *et al*., 2002a, b, 1998; Kazanskiy *et al*., 2005, 2014; Kazanskii and Kolpakov, 2009; Golub *et al*., 1995; Pavelyev *et al*., 2007; Kazanskii *et al*., 2004, 2007; Abul'khanov *et al*., 2011, 1993; Bezus *et al*., 2011a, b) conditions necessity of choosing a concrete way of microrelief creation as early as at the stage of DOE design. A binary microrelief is the simplest to form but blunt "binarying" of the DOE phase function not always allows to preserve required efficiency of an optical element. This was demonstrated by a diffractive research of binary focusators directed at a semiring and a segment with linear distribution of intensity along a focusing segment. The required intensity distribution breakdown was revealed: emerging of a focus ring instead of a semiring, absence of linear growth of intensity along a segment and other negative developments in binary focusators focal regions (Kazanskiy and Soifer, 1994). To eliminate such negative developments special design methods were suggested (Doskolovich *et al*., 1995e); these methods allow to increase effectiveness of binary DOE and extend binary microreliefs application field.

The choice of the best solution for concrete internal parameters (in this case parameters of discretization and quantization of the phase function) of a problem is effectively made on the basis of computational experiment results.

TECHNOLOGIES OF DIFFRACTIVE MICRORELIEF FORMATION

For making of designed focusators many methods and technologies of diffractive microrelief formation were developed (Popov, 1989; Volkov *et al*., 2002a, b, 1998; Kazanskiy *et al*., 2005, 2014; Kazanskii and Kolpakov, 2009; Golub *et al*., 1995; Pavelyev *et al*., 2007; Kazanskii *et al*., 2004, 2007; Abul'khanov *et al*., 2011, 1993; Bezus *et al*., 2011c, d). The choice of a technology depends on the focused radiation wave length, focusator's material and required laser power. Chronologically, the following methods became widely used: hardbaking of dichromated gelatin (Popov, 1989), dark growth in layers of liquid polymerizable compositions (Volkov *et al*., 2002a), layer-by-layer building-up of photoresist (Volkov *et al*., 1998), plasmochemical and chemically-assisted ion beam etching, electron-beam lithography (Volkov *et al*., 2002b; Kazanskiy *et al*., 2005, 2014; Kazanskii and Kolpakov, 2009; Golub *et al*., 1995; Pavelyev *et al*., 2007; Kazanskii *et al*., 2004, 2007), NC cut (Abul'khanov *et al*., 2011, 1993), plasmon nanolithography (Bezus *et al*., 2011c, d), etc. Tshe choice of the best diffractive microrelief formation method for concrete internal parameters (in this case parameters of discretization and quantization of the phase function) of a problem is effectively made on the basis of computational experiment results.

For work with high power technological lasers, it is reasonable to process focusators working surface with the help of technological methods connected with metal removing (polishing, smooth finish and lathe work), because in this case a focusator's body is made of a solid workpiece (as a rule of Oxygen-Free copper Cu-OF) (Abul'khanov *et al*., 2011, 1993) in which coolant ducts are made. Analysis of submicron unevennesses of the focusator's microrelief showed that the best results are achieved with the help of smooth finish and polishing. Technological limits of smooth finish and polishing can be observed in unguaranteed metal removal from the microrelief surface which impairs accuracy of its processing. In this case, there is no possibility to process zones of undercut of a microrelief, that is such its fragments on which microrelief cylindrical walls are conjugated with surfaces designed to reflection of laser radiation.

Because of specified reasons for focusators surfaces processing it is reasonable to use a cutting edge of natural diamond. Processing of a microrelief with the help of microcutting can provide the accuracy of focusator's work surface making >0.1 μm. Microrelief should be made with the help of microcutting at the final stage in two stages. At the first stage, we form a microrelief with the accuracy of not <1 μm with machining equipment using roller bearings or slider bearings and also plain slideways (Abul'khanov *et al*., 2011, 1993). Then the final processing of the microrelief is performed with depth of cut >0.1 μm. Finishing treatment of the microrelief may be performed in two cuts. Amount of cuts depends on microrelief height which is defined by the focused laser radiation wave length.

TECHNOLOGICAL ERRORS ANALYSIS

When impact of discretization and quantization of the phase function on focusator's work can be researched within the framework of the scalar theory of diffraction, impact of minor technological errors of the diffractive microrelief on quality and effectiveness of focusing can be estimated only within the framework of a strict electromagnetic theory, i.e., on the basis of Maxwell's equations solution (Born and Wolf, 1968). For solving of this problem a range of difference schemes (Golovashkin *et al*., 2004), transparent radiating conditions (Golovashkin and Kazanskii, 2007), Net Domain Decomposition Method (Golovashkin and Kazanskiy, 2009) cloud (Kazanskiy and Serafimovich, 2012a, b) and GPGPU-services (Golovashkin and Kasanskiy, 2011) were developed. The developed set of information processing methods allowed to estimate the impact of errors of microrelief formation in the course of laser ablation of polycrystalline diamond films on the functioning of transmitting focusators of infrared band laser radiation (Pavelyev *et al*., 2006).

CREATION OF NEW CLASSES OF DOE

Methods which had been developed for focusators turned out to be effective for creation and studying of new classes of diffractive optical elements such as multifocal (Golub *et al*., 1992c; Soifer *et al*., 1994) and spectral DOE (Doskolovich *et al*., 2005a, 2007a) optical antennas (Golub *et al*., 1989b; Kazanskiy *et al*., 2000b, c;

Doskolovich *et al.*, 2004) diffractive beam splitters (Kazanskiy and Skidanov, 2012), etc. (Golub *et al.*, 1988b, 1990; Khonina *et al.*, 2011b, c). In particular, mathematical modelling means (before the optical experiment) demonstrated capability of working of the whole DOE's aperture on a composite focal region and also effective functioning of multifocal DOE forming (as distinct from composite DOE) focal lines which are several times thinner. Also, we observed working capacity of spectral DOE forming required distributions of intensity under lighting with monochromatic beams with certain wave lengths from the preset (Doskolovich *et al.*, 2005a, 2007a). Optical antennas appeared to be effective elements of lighting technology devices (Kazanskiy, 2002; Doskolovich *et al.*, 2005a, 2007a; Moiseev *et al.*, 2011; Aslanov *et al.*, 2013).

EXPERIMENTAL RESEARCHES

Nevertheless, analytical methods of researching and careful mathematical modelling are just preparatory research methods. Final decision on possibility of this type of focusing, working capacity of multifocal or spectral DOE, binary beam splitters or optical antennas is taken in view of optical experiment results. Experimental validation of quality passes through all stages of focusators creation. The initial stage is dedicated to cleanness and optical flatness of the base used. For this purpose special methods based on analysis of behaviour of a drop of liquid falling onto the base surface (Borodin *et al.*, 2005, 2009), tribometrical (Kazanskiy *et al.*, 2008a, b), interferential and other approaches (Kazanskiy, 2006, 2012) were developed.

Also, we should note development of methods of microrelief form control (Babin *et al.*, 2009) and different optical schemes and devices for DOE experimental research (Volkov *et al.*, 2001; Golub *et al.*, 1991d; Kazanskiy *et al.*, 2000; Doskolovich *et al.*, 2007c; Karpeev *et al.*, 2007). The most important proof of effectiveness of the developed information and optical technologies is a fair congruence of data of computational and physical experiments for focusator directed at a ring (Doskolovich *et al.*, 2002), diffractive lens (Golub *et al.*, 1991d), different focusators (Kazanskiy *et al.*, 2000d), spectral DOE (Doskolovich *et al.*, 2007c), fiber-optic sensors (Karpeev *et al.*, 2007) and binary beam splitter (Kazanskiy and Skidanov, 2012).

TECHNOLOGIES OF FOCUSATORS APPLICATION

One of the most important ways of practical using of diffractive computer optics is technological application of focusators. As examples of such ways we can mention laser quenching (Sisakyan *et al.*, 1990; Doskolovich *et al.*, 1993), buildup, marking (Doskolovich *et al.*, 1991), formation of nanopore structurs of crystalline (Kazanskiy *et al.*, 2008c) and metal (Kazanskiy *et al.*, 2011; Murzin, 2013) materials and so on. A focusator directed at a ring (Golub *et al.*, 1988a; Soifer, 2013) is used in the installation for growing monocrystalline fibers with the help of a minipedestal method (Bufetova *et al.*, 2006); this installation was developed in the Institute of General Physics of the Russian Academy of Sciences for creation of solid state neodymium lasers. This installation, based on ring laser heating, provides production of high-quality fibers of activated monocrystals with a controlled radial refraction index gradient. A focusator in a set of rings is used for 3D-control of spacer grids of atomic reactor fuel assemblies (Finogenov *et al.*, 2007).

Obtained theoretical and laboratory results found practical use in the real production. Application of focusators allowed to perform thermal quenching of a cutting edge of an edge tool of a complex space form (Soifer *et al.*, 2007). Application of focusators allowed to substantially reduce time spent for thermal quenching and energy consumption too.

Many systems and devices binding edge tool cutting edge corner to a coordinate testify to that this technological problem is still actual. Milling tools used in metalworking have several cutting edges for metal removing. Degree of wear of each cutting edge determines cost effectiveness of milling technological operation and also quality of a surface layer of a piece processed with the help of milling cut. There is no information on means of controlling state of each milling cutter cutting edge right during the processing. Focusators application allows to solve two above mentioned problems at the same time (Abul'khanov *et al.*, 2009), i.e. at the same time to bind a cutting edge corner to a coordinate and to estimate wear degree of each tool's cutting edge. Besides, focusators allow to monitor wear degree of coatings covering the cutting edge.

Acoustic waves focusators give possibility to implement vibration isolation for a specified vpm range and selectively, i.e. for an intended frequency harmonic (Abul'khanov *et al.*, 2012) and that allows to set technological equipment for solving a concrete problem delicately and to a maximum degree of effectiveness. Vibrations applied to tool's zone of contact with a working surface reduce cutting force and that increases energy effectiveness of technological processing, lowers temperature in cutting zone which results in increasing of qualitative parameters of a piece surface layers and also tool hardening. Focusators provide vibrations of required frequency and amplitude on a surface of a specified shape. In this case, we may achieve vibration frequency not obtainable for other sources of vibrations used in the production and that allows to lower temperature in smooth finish zone. At that burns are avoided, temperature is much lowered in the zone of grinding wheel's contact with a piece's surface, grinding wheel's resistance is improved, we observe no loading of grinding wheel's cutting edge (Evdokimov *et al*., 2014; Perez *et al*., 2008; Skuratov *et al*., 2007).

Giving high-frequency vibrations of small amplitudes to the diamond indentor's zone of contact with a working surface allows to substantially decrease the friction coefficient in the contact zone (<0.2) and that practically eliminates heating under piece's surface strain hardening with a diamond sphere. Besides, high-frequency vibrations provide decrease of sizes of hardened metal metallographic structure grains and that in its turn affects piece's performance characteristics favourably.

Focusators allow to give vibrations not only to a surface but also to some space. This property was used for mixing abrasive grains of different fractions up to a high degree of homogeneity (Abul'khanov *et al*., 1993; Soifer *et al*., 2011).

Focusators application in the engineering technology allowed to align large and box-type workpieces with machine accessories spindle rotation axis to high precision and also to align optical pieces to high precision too (Abul'khanov *et al*., 1994).

CONCLUSION

Developed methods, devices and technologies allowed not only to solve a wide range of problems of creation and research of focusators but also to start designing effective machine vision systems (Volotovskii *et al*., 2005; Izotov *et al*., 2011; Kazanskiy and Popov, 2010, 2012) investigating unique properties of diffractive nanophotonics components (Kazanskiy *et al*., 2010, 2013; Serafimovich *et al*., 2013; Khonina *et al*., 2013; Kazanskiy and Serafimovich, 2014; Glushchenko *et al*., 2011, 2013; Bykov *et al*., 2010) and creating promising information technologies on this basis (Soifer, 2014) and also to proceed to development of new high-efficiency technological processes.

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