OPTICAL MEASURING AND LASER TECHNOLOGIES FOR SCIENTIFIC AND INDUSTRIAL APPLICATIONS

Yu.V. CHUGUI[1, 2, 3]**, A.G. VERKHOGLYAD*[1]*, P.S. ZAVYALOV*[1]*, E.V. SYSOEV*[1]*, R.V. KULIKOV*[1]*,*
M.A. ZAVYALOVA[1]*, A.G. POLESHCHUK*[4] *and V.P. KOROLKOV*[4]

1 Technological Design Institute of Scientific Instrument Engineering, Siberian Branch
of the Russian Academy of Sciences (TDI SIE SB RAS),
41, Russkaya str., Novosibirsk, 630058, Russia, Tel.: +7 (383) 306-58-95, Fax: +7 (383) 306-58-69
E-mail: chugui@tdisie.nsc.ru
2 Novosibirsk State University, 2, Pirogova str., Novosibirsk, 630090, Russia
3 Novosibirsk State Technical University, 20, K. Marksa pr., Novosibirsk, 630073, Russia
4 Institute of Automation and Electrometry, Siberian Branch of the Russian Academy
of Sciences (IAE SB RAS), 1, Academician Koptyug pr., Novosibirsk,630090, Russia

Abstract:

Modern industry and science take novel 3D optical measuring systems and laser technologies with micro-/ nanometer resolution for solving actual problems. Such systems, including the 3D dimensional inspection of ceramic parts for electrotechnical industry and 3D superresolution low-coherent micro-/nanoprofilometers are presented. New approach for the formation of 3D laser templates for large-sized objects such as antennas using diffractive optics is presented. The newest results in the field of laser technologies for high-precision synthesis of microstructures by updated image generator using the semiconductor laser are presented. The measuring systems and the laser image generator developed and produced by TDI SIE and IAE SB RAS have been tested by customers and used in different branches of industry and science.

Keywords: 3D Optical Inspection, Low-Coherent, Diffractive Optical Element, Pico Resolution

1. INTRODUCTION

Solving many actual problems in space, atomic, electrotechnical, microelectronic, opto-mechanical branches of industry, as well as in science takes high-production noncontact 3D optical measuring systems and laser technologies with micro-/ nanoresolution [1].

For microelectronic industry we have developed and produced the optoelectronic device for efficient 3D inspection of geometrical parameters of ceramic parts, including internal and external rings diameters and coaxiality of these diameters, rings height, flatness and parallelism of ring face surfaces as well as detection of defects on their face surfaces.

The method of light template formation for large-sized objects (from several to tens of meters), such as space antennas has been developed on the basis of diffraction optical elements, which generate in set of light markers (several hundreds) in the form of crossed laser beams.

Technical performances of nanoprofilometer using low-coherent interference method with very high resolution are presented. Using a perfectly atomic-smooth mirror in interferometer reference arm, subatomic resolution of 20 picometers in-depth has been achieved.

For synthesis of high-precision microstructures on flat and curvilinear surfaces TDI SIE and IAE SB RAS have developed and produced commercial model of the updated circular image generator using semiconductor laser. Effective application of this generator is fabrication of diffractive optical elements for 3D measurement systems. A wavefront error (rms) reconstructed by these elements is about $\lambda/100$. The experimental results for these technologies are presented.

2. OPTOELECTRONIC DEVICE FOR 3D DIMENSIONAL INSPECTION OF CERAMIC PARTS

Technical ceramic parts are widely used in different branches of industry: nuclear, electronics, electrotechnical ones, etc. A considerable part of them are ceramic parts with diameters from 10 to 50 mm and thickness from half millimeter to several tens of millimeters (Fig. 1). In many cases these parts have to be produced with high precision (gap tolerance is 10 – 50 µm).

Fig. 1: Ceramic parts under 3D dimensional inspection

Instead of traditional contact methods with known shortcomings (wear of measuring instruments, deformation and even damage of parts, etc.), we have developed automatic optoelectronic device for 3D noncontact inspection of all geometrical parameters of ceramic object‘s family.

The measurement principle of the ring parts sizes is illustrated by the optical scheme in Fig. 2. For dimensional inspection of these parts we have used three methods: shadow method for measurement of internal and external rings diameters and coaxiality of these diameters, structured light method using diffractive optical element (DOE) for measurement of rings height, flatness and parallelism of their face surfaces, as well as TV method for detection of defects on face surfaces.

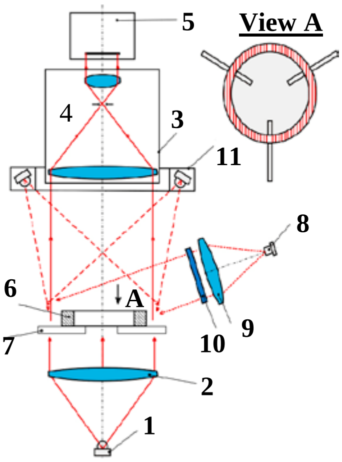


Fig. 2: The optical scheme of device for 3D ceramic rings inspection using shadow, structured light and TV methods: 1 – LED, 2 – collimating lens, 3 – telecentric objective, 4 – aperture diaphragm, 5 – digital camera, 6 – inspected part, 7 – table, 8 – semiconductor laser, 9 – collimating objective, 10 – diffractive optical element (DOE), 11 – the ring illuminator

The structured light method formed by DOE (the ray tracing is shown in Fig. 3) is used for measurement of flatness and parallelism face surfaces and rings thickness. DOE focuses the laser radiation on ring as 46 light lines with 1 mm step. To ensure the equal conditions in all measurement range, the incident angle of the rays α and the angular aperture Δα for each line have to be identical. The lighting geometry is calculated in such way that the diffraction zero order goes aside from measuring position. DOE was produced by laser circular writing system CLWS-300C/M developed at TDI SIE [2]. Due to binary phase version of DOE its diffractive efficiency is about 40%.

For JSC “NEVZ” (Novosibirsk, Russia) we have developed and produced industrial prototype of the optoelectronic system RING for ceramic rings inspection (Fig. 4), which has been operating successfully since 2011.

The technical characteristics of RING system are the following: measuring range of diameters from 20 to 45 mm and thickness from 0.8 to 10 mm; measurement error of ring geometrical parameters (confidential probability is 0.95): external and internal diameters are ± 0.006 mm, height is ± 0.002 mm, nonflatness of each face is ± 0.006 mm and nonparallelism of two faces is ± 0.008 mm. The measurement time is 8 s.

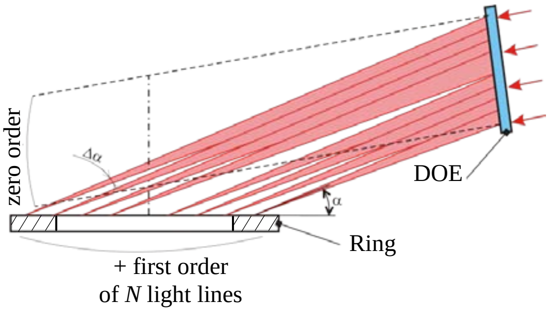


Fig. 3: Formation of the structured light using the diffractive optical element for inspection of object‘s flatness and parallelism

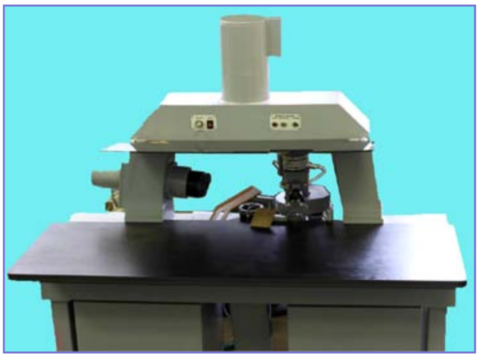


Fig. 4: Optoelectronic system RING for 3D ceramic rings inspection

3. THE FORMATION OF 3D LASER TEMPLATES FOR LARGE-SIZED OBJECTS USING DIFFRACTIVE OPTICS

The method of light template formation for large-sized objects (from several to tens of meters) such as antennas has been developed on the basis of diffractive optical elements. It takes to adjust about thousand nodal points, therefore the distance between them is from 100 mm up to 1000 mm. Such operation is very responsible and labor-consuming and is carried out by several operators at the same time during many days. Alternative way is to use for antenna adjustment the 3D laser template which generates in space the positions of the nodal points of the antenna with high accuracy.

The proposed method [3] is based on formation in space the pairs of the focused laser beams which are crossed on the paraboloid surface describing the antenna configuration (Fig. 5).

The antenna nodal points are formed by two or three diffractive optical elements, each of which creates N focused laser beams. At nodal shift in Z-direction the focusing point at small shifts will increase in sizes, and at the considerable shifts this point will be divided.

The main advantage of this method in comparison with laser projection available in the market is potentially higher precision due to DOE’s capability to generate the wavefront with very high accuracy (deviation is λ/10 – λ/100). At distances of 20-30 m such deviations of the wavefront will lead to spot shift about 0.02-0.2 mm.

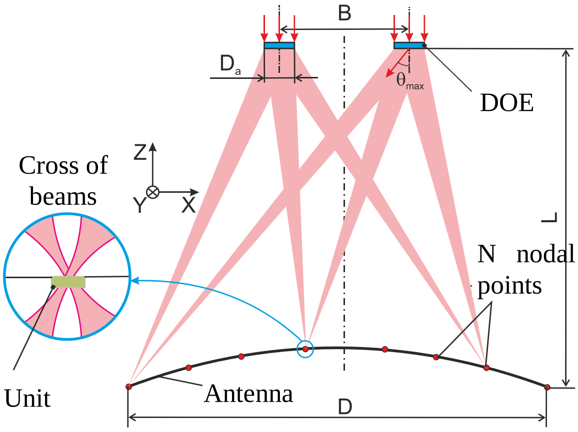


Fig. 5: Principle of 3D laser template formation under antenna inspection

In experiments we used two types of laser sources with the stabilized wavelength: He-Ne laser (λ = 628 nm, power is 1 mW) and the solid-state laser (λ = 532 nm, power is 100 mW). The basic distance *B* was equal to 250 mm and 500 mm (Fig. 6). One can see that at *B* = 250 mm the shift Δz = 2 mm of the observation plane on depth leads to increasing the spot size about 10-20% (Fig. 6a) that is well observed by an eye. In case of the shift Δz = 4 mm the spot takes the oval form, and at big shifts it starts sharing on two parts. The same effects take place for case of *B* = 500 mm, but under less shifts Δz due to more high sensitivity (in two times) of the optical scheme. The obtained results confirm the feasibility of the offered method for the large-sized objects geometry inspection using DOE.

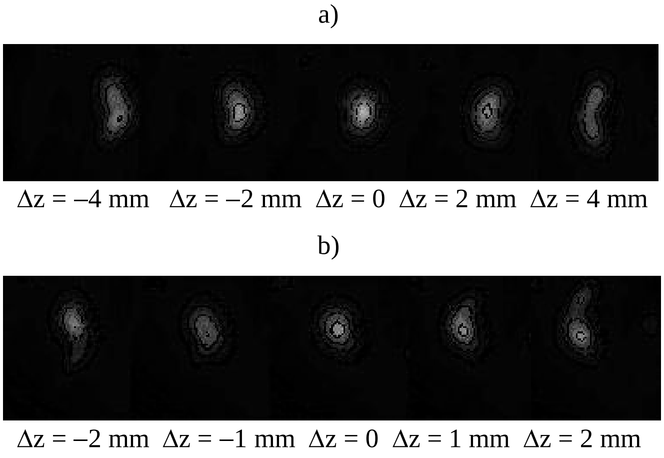


Fig. 6: The experimental pictures in caustic zone of the crossed beams at various shifts Δz for two basic distance *B*: 250 mm (a) and 500 mm (b)

4. 3D SUPERRESOLUTION OPTICAL MICRO-/NANOPROFILOMETRY

Measurement of metallic surfaces local profile is urgent problem in many branches of industry especially for the profile inspection of 3D produced details and their surface defects with micrometer-/ nanometer resolution. TDI SIE has more then twelve years experience as for development and production of an industrial version of the white-light profilometers.

The principle of object surface profile measurement is based on the interference phenomenon of partially-coherent (in time) light waves, emitted by polychromatic light source (e.g. filament lamp). Measuring device scheme based on Michelson interferometer is shown in Fig. 7, a, b [4].

The position and lateral configuration of interference area ($X \times Y$) on CCD matrix is determined by intersection of reference surface and surface under measurement. This intersection determines the isoline, corresponding to the given depth along the axis *Z* in the direction of beam light incident on object. The registration of these areas by CCD camera allows reconstructing this isoline (Fig. 7, b). To obtain 3D model of the inspected objects there is high precision scanning procedure in depth *Z* by the change of mutual location of surface under measurement and interferometer unit.

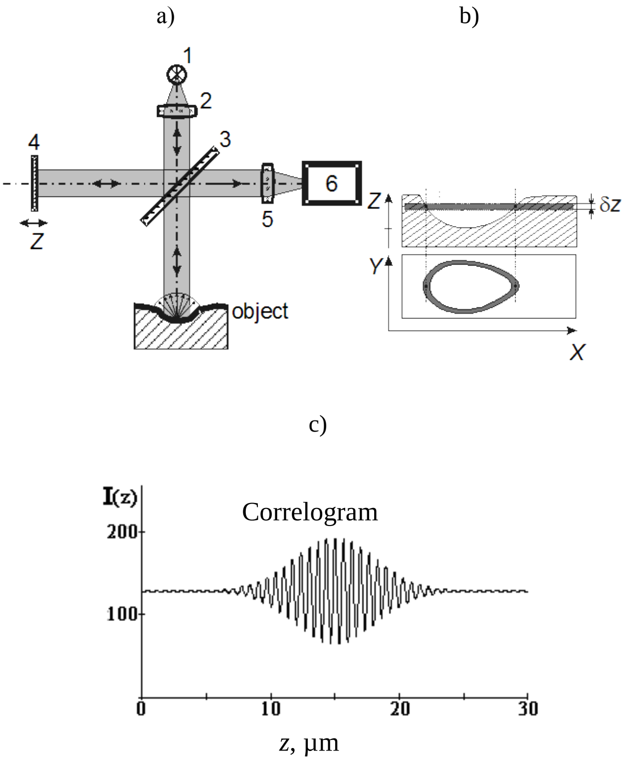


Fig. 7: Surface profile measurement principle by white-light interferometry: Michelson interferometer (a), isoline formation (b), correlogram for the coherence length ≈ 15 µm (c): 1 – white-light source, 2 – collimator, 3 – split mirror, 4 – reference arm mirror, 5 – objective, 6 – CCD camera, $I(z)$ is the correlogram intensity

We have developed and produced industrial version of the low-coherent profilometer PROFILE for 3D surface inspection within the range of 0.005 – 10 mm with resolution of 0.1 µm (Fig. 8). These systems have been operating successfully for eleven years under workshop conditions in atomic industry.

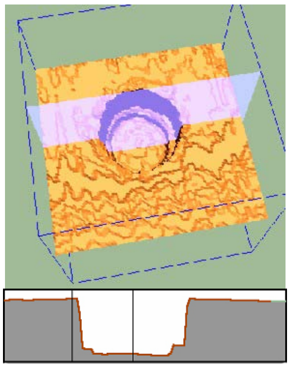


Fig. 8: 3D reconstructed bore hole in metal. Area is 0.43 × 0.43 mm^2, lateral size is 106 μm, depth is 115 μm

In 2010 the TDI SIE has developed new type of measuring system – white-light microscope intended both for measurements of micro- and nanoprofile of surfaces by processing of correlograms (Fig. 7, c). In this case under scanning interferometer field within a few nanometers, correlogram is found from the set of interference patterns for each point of nanosurface [5].

The correlogram maximum corresponding to a zero path-length difference of light waves scattered by adjacent surface parts in the reference and measuring arms of the interferometer determines the absolute axial position of the measured surface part. The scanning range depends on the coherence length of the light source and can reach tens of microns.

Fig. 9: Interference micro- / nanoprofilometer MNP-1

Microscope (Fig. 9) operates in nano- and microregimes. Nanomeasurement regime (Fig. 10) is intended for measurement of surfaces relief height (surface finish class) up to 50 μm with resolution of 0.1 nm. As for micromeasurement regime the microscope measures “rough” surfaces relief height with the same specifications as PROFILE system.

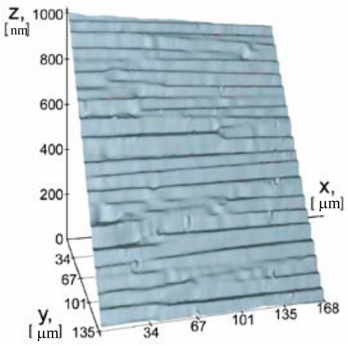


Fig. 10: Sample of stepped nanorelief structure on Si material. Height of atomic step is varied from 5 nm to 80 nm

Using in interferometer reference arm a perfectly (atomic-smooth) mirror (produced by Institute of Semiconductor Physics, SB RAS), as well as program-algorithmic software, the breakthrough under measurement of relief height with resolution of 20 picometers and better has been realized (Fig. 11). 3D-relief of stages (steps) with the height of 1 atom has been reconstructed [6]. The results obtained are the base for metrological tasks solution in nanometer range, as well as for development of the effective noncontact measuring devices with subatomic in-depth resolution.

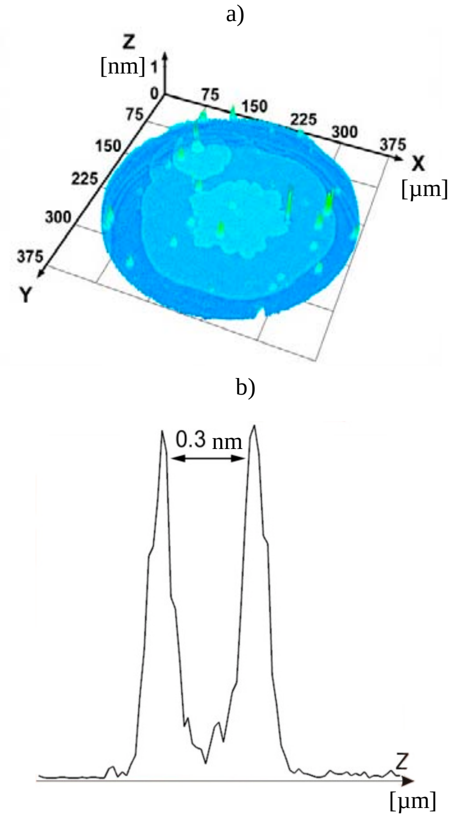


Fig. 11: The reconstructed relief of 3D nanoobject (a) and heights histogram (b) under measurement of one-atomic steps on Si crystal surface

Application of these micro-/nanoprofilometers are very effective for science, including study of nanostructures and nanomaterials, measurement of film thickness, surface inspection of different polymers, micro crack detection and nanometrology. These profilometers are used also at some institutes of Siberian Branch of the Russian Academy of Sciences for scientific researches.

5. UPDATED LASER CIRCULAR IMAGE GENERATOR

TDI SIE and Institute of Automation and Electrometry SB RAS jointly have developed new model of circular laser pattern generator using a semiconductor laser for synthesis of high-precision microstructures on flat and curvilinear surfaces.

Laser image generator is working in polar coordinates. The principle of its operation is based on forming the patterns on rotated substrate with photoresist coating by focused laser beam in the mode of circular raster scanning (Fig. 12). The substrate is placed on high-precision spindle, which is rotated by motor and controlled by spindle module. Laser beam is focused on the substrate by a writing microscope head and its power is changed by acousto-optic modulator under drive control. Radial displacement *R* is realized by high-precision air bearing carriage where laser modulator and writing microscope head are placed. This displacement *R* is measured by laser interferometer. The writing of information on curvilinear surfaces is fulfilled by movable writing microscope head (in vertical *Z* direction) using autofocus module. High accuracy of elements topology synthesis is reached by the precision control systems.

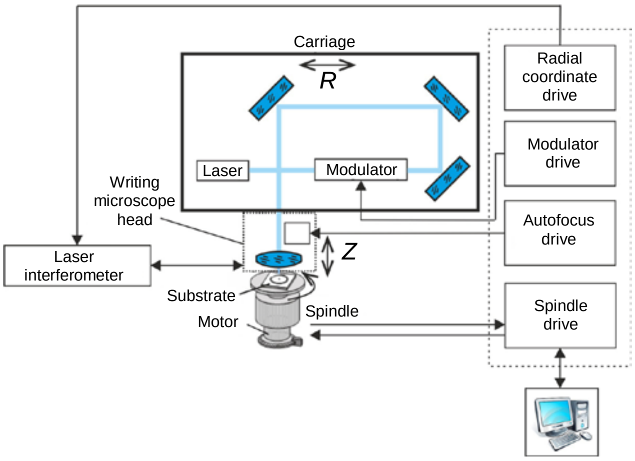


Fig. 12: Structure scheme of laser image generator using semiconductor laser

Placement of current-modulated semiconductor UV laser (λ = 405 nm) and optical channel on linear coordinate stage of updated pattern generator allows (as compared with our previous model of laser pattern generator CLWS-300 with argon laser) [2, 7] improving a focused beam pointing stability, reducing the optical channel length, and avoiding problems connected with water cooling. Multichannel modulation including analog, digital direct laser current and acousto-optic ones broadens a dynamic range of laser beam intensity which is required due to large range of linear speed at raster scanning.

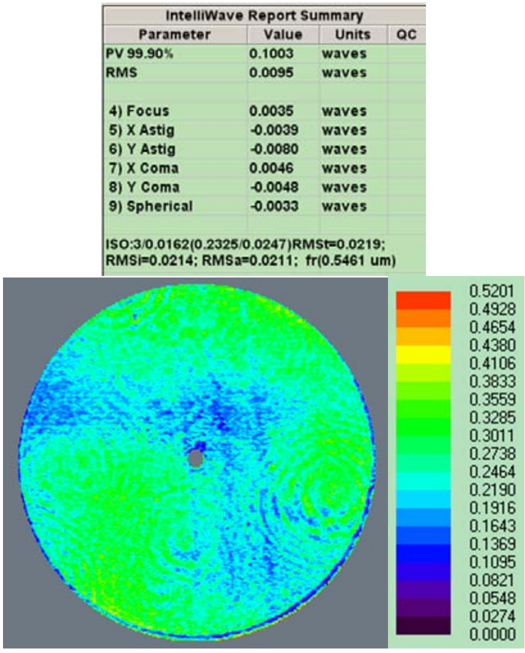
We have produced pilot sample of laser image generator using semiconductor laser for Harbin Institute of Technology (P.R. China) in 2011 year. As a result of testing of this generator the following main specifications were obtained: working field diameter is 250 mm, spatial resolution is up to 1000 lines/mm, resolution on radial coordinate is no worse than 1 nm, angular coordinate measurement resolution is up to 0.25”, displacement range on vertical coordinate is up to 25 mm, autofocusing error is ± 0.05 µm. Maximum tilt of curved surface is 10º.

This system allows one to form diffractive elements, computer-synthesized holograms, gratings, limbs, and different photomasks of arbitrary topology on plane and axially symmetric curvilinear surfaces (Fig. 13).

This updated laser pattern generator is more compact and has the decreased temperature drift due to special rearrangement of mechanical units. The additional advantages of this generator are the following: periodical rotation center search by means auxiliary red laser beam with high beam pointing stability, and procedure of interferometer wavelength recalculation during writing process on the base of environment temperature and air pressure. Controlling software allows one to fabricate binary and continuous relief 3D structures on convex and concave surfaces covered by photoresist or photoresist/Cr layers. The updated system can be easily added by second writing laser with 532 nm wavelength which is applied for thermochemical direct writing on Cr films without photoresist. Such process is optimal for high precision computer-synthesized holograms fabricated on large and thick substrates which are not suitable for photoresist spinning.

Fig. 13: The updated pattern generator using semiconductor UV laser

Example of wavefront distortion map for manufactured binary diffractive lens is depicted in Fig. 14. Wave front error (rms) is about λ/100.



IntelliWave Report Summary			
Parameter	Value	Units	QC
PV 99.90%	0.1003	waves	
RMS	0.0095	waves	
4) Focus	0.0035	waves	
5) X Astig	-0.0039	waves	
6) Y Astig	-0.0080	waves	
7) X Coma	0.0046	waves	
8) Y Coma	-0.0048	waves	
9) Spherical	-0.0033	waves	

ISO:3/0.0162(0.2325/0.0247)RMSt=0.0219;
RMSi=0.0214; RMSa=0.0211; fr(0.5461 um)

Fig. 14: Report summary (from Intellium Z100 interferometer) and wavefront distortion map for the diffractive lens manufactured by the updated laser image generator

6. CONCLUSION

For electrotechnical industry the TDI SIE has developed and produced the optoelectronic device RING for high-productive 3D noncontact inspection of ceramic parts. The system RING has been operating successfully since 2011.

The method of light template formation for large-sized objects (from several to tens of meters) such as antennas has been developed on the basis of diffractive optical elements. The proposed method can greatly facilitate the implementation of labor-intensive assembly operations, adjustment as well as inspection the shape of large-sized antennas in workshop conditions.

For scientific and industrial applications TDI SIE has developed and produced two models of 3D optical superresolution profilometers using low-coherent interference method. One of them device PROFILE is intended for 3D microprofiling of different objects with resolution of 0.1 μm in wide range up to 10 mm. These profilometers have been operating successfully for eleven years in atomic industry.

The second profilometer model MNP-1 can work in microrange like PROFILE and as well as in nanorange with measurement resolution of 0.1 nm within dynamic range of 50 μm. Using a perfectly atomic-smooth mirror in interferometer reference arm as well as program-algorithmic software, the breakthrough under measurement of relief height with subatomic record resolution of 20 picometers in-depth and better has been achieved. This profilometer can be effectively used in nanoindustry.

For synthesis of high-precision microstructures on flat and curvilinear surfaces TDI SIE and IAE SB RAS have developed and produced commercial model of the updated circular image generator using semiconductor laser. High accuracy of elements topology synthesis is reached by the precision control systems. The generator allows one to produce the computer-synthesized holograms on plane and axially symmetric curvilinear surfaces, the gratings, the limbs, and different photomasks of arbitrary topology with spatial resolution up to 1000 lines/mm within the working field diameter 250 mm. Effective application of this generator is fabrication of diffractive optical elements for 3D measurement systems. As shown, wavefront error (rms) reconstructed by these elements is about λ/100.

The obtained results are applied to many industrial fields, including mechanical engineering, optomechanical, electrotechnical, microelectronic, automobile branches of industry, mechanical engineering, hydropower engineering, space, as well as to science.

REFERENCES

[1] Gordon M. Brown, Kevin G. Harding, Philip H. Stahl, “Industrial Application of Optical Inspection, Metrology, and Sensing” *Proc. SPIE*, vol.1821, 1992.

[2] V.M. Gurenko, L.B. Kastorsky, V.P. Kiryanov et al, “Laser writing system CLWS-300/C-M for microstructure synthesis an the axisymmetric 3-D surfaces”, *Proc. SPIE,* vol.4900, pp. 320-325, 2002.

[3] P.S. Zavyalov, Yu.V. Chugui, “The formation of light templates for large-sized objects using the diffraction optics methods”, *Computer Optics*, vol.37, No4, pp. 419-425, 2013 (in Russian).

[4] R.V. Kulikov, E.V. Sysoev, “Microrelief Measurements for a White-Light Interferometer with Adaptive Algorithm Interferogram Processing”, *Key Engineering Materials : Measurement Technology and Intelligent instrument IX*, vol.437, pp. 35-39, 2010.

[5] E.V. Sysoev, “White-Light Interferometer with Partial Correlogram Scanning”, *Optoelectronics, Instrumentation and Data Processing*, vol.43, No1, pp. 83-89, 2007.

[6] Yu.V. Chugui, A.V. Latyshev, S.N. Makarov, S.V. Plotnikov, E.S. Senchenko, E.V. Sysoev, A.G. Verkhogliad & P.S. Zav’yalov, “3D optical measuring technologies for scientific and industrial applications”, *Proc. LMPMI-2011*, pp. 13-22, Braunschweig, Germany, Sept. 2011.

[7] Yu.V. Chugui, V.P. Kiryanov & A.G. Verkhogliad, “High-performance Laser Technological Processing Systems for Scientific and Industrial Applications”, *Proc. MATADOR Conference*, pp. 139-146, Taiwan, China, July 2007.