FABRICATION OF HIGH EFFECTIVE POWER SILICON DIFFRACTIVE OPTICS OF TERAHERTZ RANGE BY FEMTOSECOND LASER ABLATION OF SILICON SURFACE

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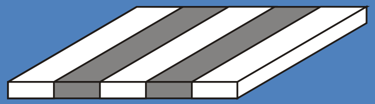
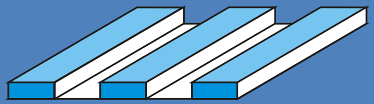
DIFFRACTIVE OPTICAL ELEMENTS (DOEs)

Key ideas: use of diffraction phenomenon;
phase reduction to interval [0, 2π); phase discretization.

Frauhhofer diffraction grating

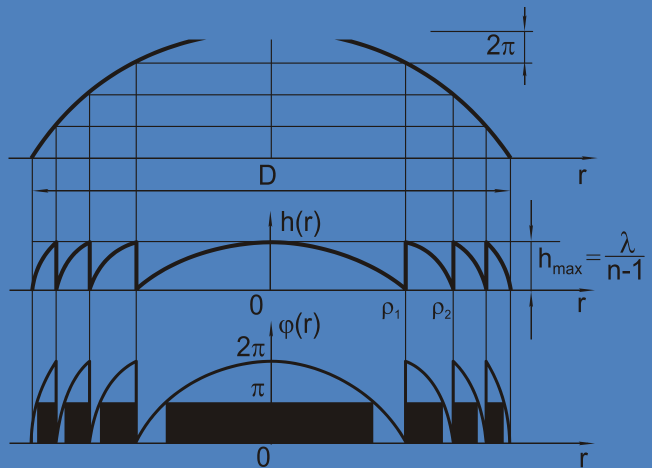


Amplitude mask



Phase microrelief

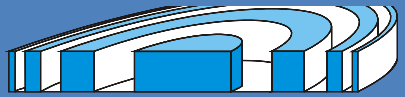
Fresnel lens



Main DOE characteristics
Wavelength; zone boundary; zone profile

Rayleigh-Soret Zone plate

Amplitude mask

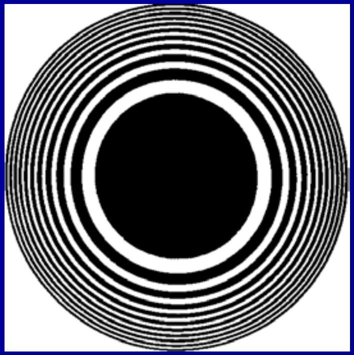


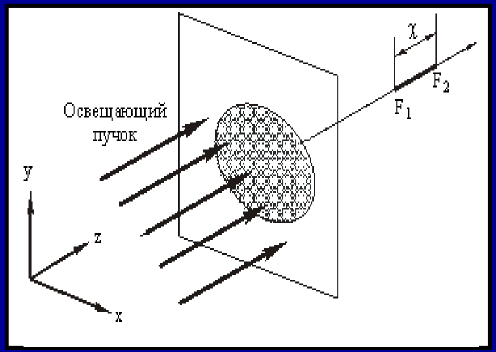
Phase relief

First diffraction gratings: 1673 — J. Gregory (the feather)
1785 — D. Rittenhouse (the hair) ; 1821 — J. Fraunhofer (the wire)
Zone plate – late XIX-th century, France.

FOCUSERS – the first elements of diffractive computer optics [1]

Key idea: solving the inverse problem
of diffraction relative to zone boundaries and size





Focuser into an axial
line, λ = 0.63 μm

A.M. Prokhorov
(1916 - 2002)

I.N. Sisakian
(1938 - 1995)

The years 1982-1984 have seen synthesis of DOEs
to select and generate spatial laser modes [2] and
Bessel optics elements [3].

[1] “Focusing the coherent radiation into a designed space region with computer-generated holograms”, *Letters to the JTP*, v. 7, No. 10,
pp. 618-623 (1981).

[2] “Synthesis of spatial filters to study the transverse mode
composition of coherent radiation”, *Quantum Electronics*, v. 9, No. 9, pp. 18066-1868
(1982).

[3] “Bessel optics”, *Proceedings of the USSR Academy of Sciences*, v. 274, No. 4, pp.
802-805 (1984).

APPROACHES AND NUMERICAL METHODS FOR DOE CALCULATION

Approaches	Numerical Methods
Geometrical optics. Eikonal equation	Analytical Methods. Asymptotics.
Helmholtz equation. Kirchhoff integral	Iterative algorithms of Gerchberg-Saxton type or IFTA. Methods of amplitude-phase coding. Methods of direct search (genetic algorithm, simulated annealing algorithm.) .
Maxwell’s equations	Finite-Difference Time-Domain method (FDTD). Rigorous Coupled Wave Analysis (RCWA)

IMPORTANT! PARTICULAR NUMERICAL METHOD IS IMPOSING OWN RESTRICTION ON THE FORM OF OPTICAL MICRORELIEF

TECHNOLOGIES AND MATERIALS

Technologies	Materials	Range
Lithography+Plasma-Chemical Etching	Silicon, diamond, quartz, glasses	from Visible to Terahertz
UV-Laser Ablation	Diamond films	Middle-IR (λ=10.6 μm)
Interference Lithography	Photoresist	Visible and Near-IR
Focused Ion Beam (FIB)	Diamond, Silicon	Visible and Near-IR
Micromechanical Processing	Glass, Quartz	from Visible to Mid-IR
Multiphoton Polymerization	Photoresist	Visible and Near-IR

NOVOFEL

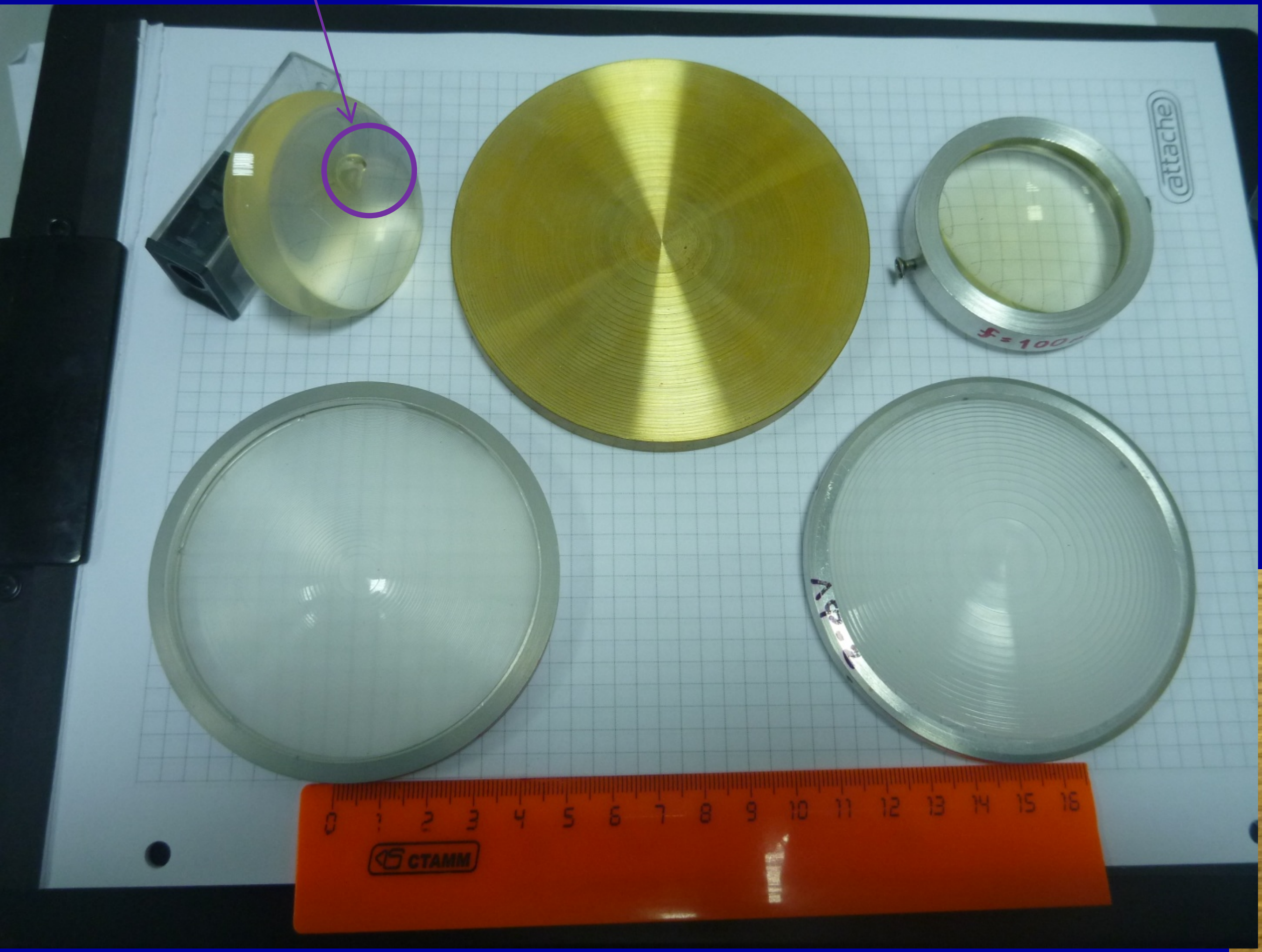
1. First working range λ=100 – 300 μm
2. Second working range λ=8 – 20 μm

Budker Institute of Nuclear Physics (Novosibirsk, Russia)

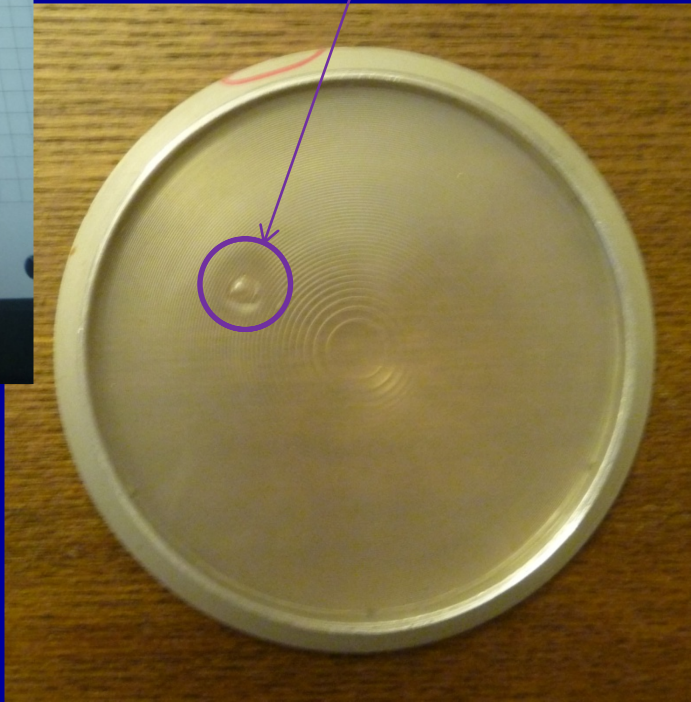
B.A. Knyazev, G.N. Kulipanov, N.A. Vinokurov Novosibirsk terahertz free electron laser: instrumentation development and experimental achievements / *Measur. Sci. Techn*. – 2010. – Vol. 21. – P. 13.

POLYMER THZ DIFFRACTIVE LENSES

Polymer lens, f = 50 мм, D = 50 мм, after illuminating by non-focused gaussian beam of NOVOFEL



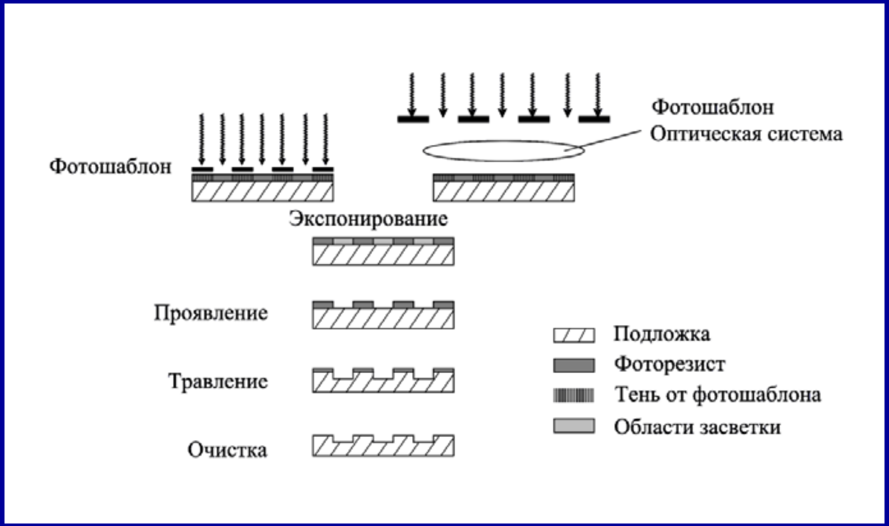
Polymer lens surface has been damaged by beam reflected from carbon surface



B.A. Knyazev, Real-Time Imaging Using a High-Power Monochromatic Terahertz Source: Comparative Description of Imaging Techniques with Examples of Application. *J Infrared Milli Terahz Waves*, V. 32, P. 1053 (2011)

LITHOGRAPHY+PLASMA–CHEMICAL ETCHING

Plasma chemical etching system ETNA-100-PT produced by NT-MDT (Russia)



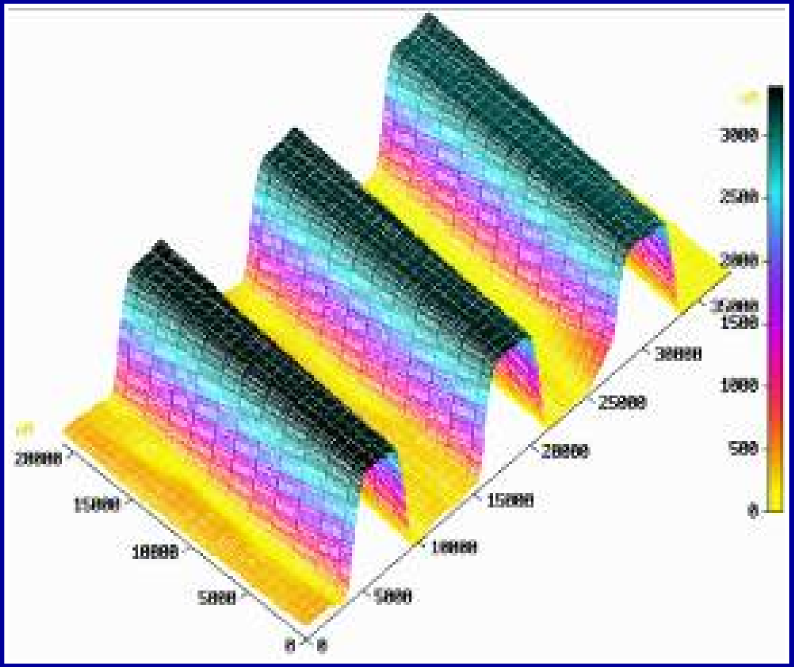
Advantages

– wide spectrum of materials (quartz, silicon, dimond, glasses),
– relatively large apertures (up to 90 mm),
–relatively large etching depth.

Disadvantages

– step–like character of relief,
– a lot of operations,
–it is a difficult to realize 3D structures.

DIAMOND DOEs FOR CO_2-LASERS



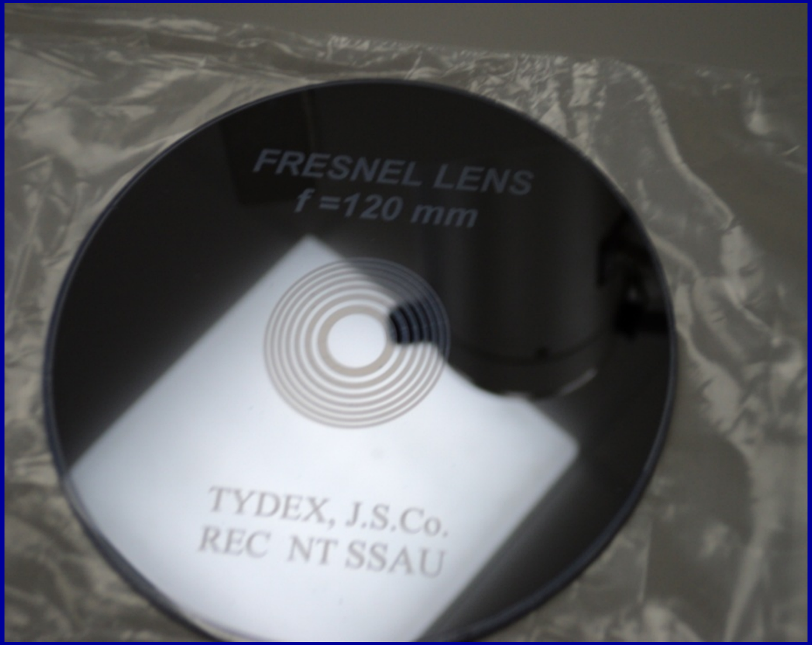
The wavelength is of λ=10,6 μm.
Maximal etching depth is nearly 7.5 μm.

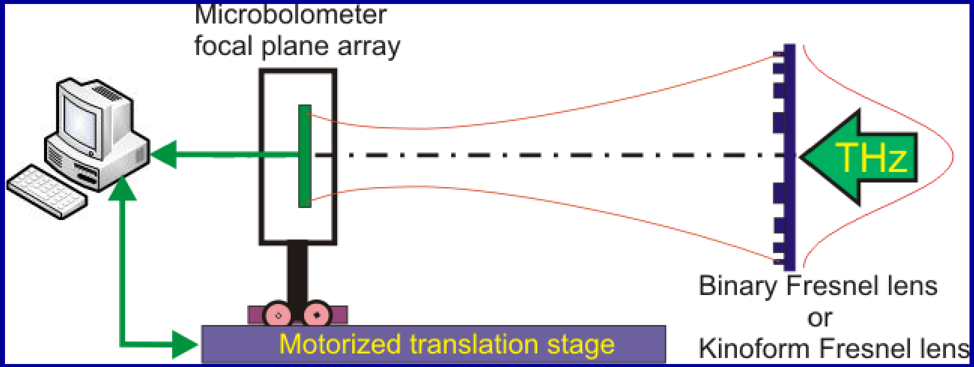
Material: polycrystalline diamond films

Technology: plasma-chemical etching.
Working gases: Ar+O2 (50% mixture).
Masking layer – niobium.

Optics & Laser Technology, 39(6) P.1234-1238 (2007)

SILICON DIFFRACTIVE OPTICAL ELEMENTS FOR FOCUSING OF TERAHERTZ BEAMS



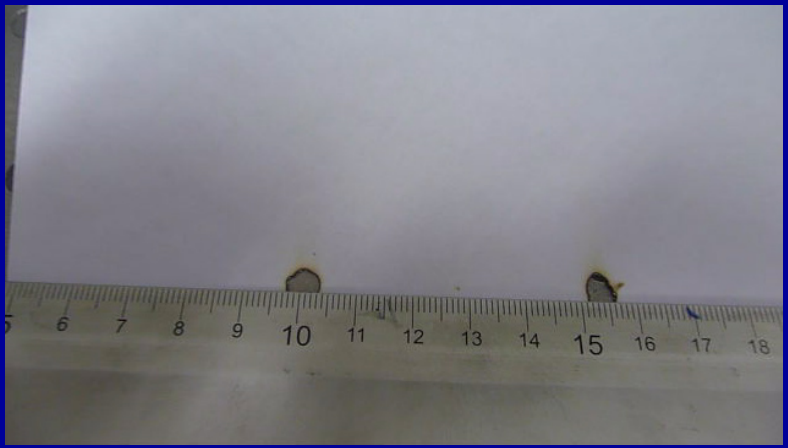


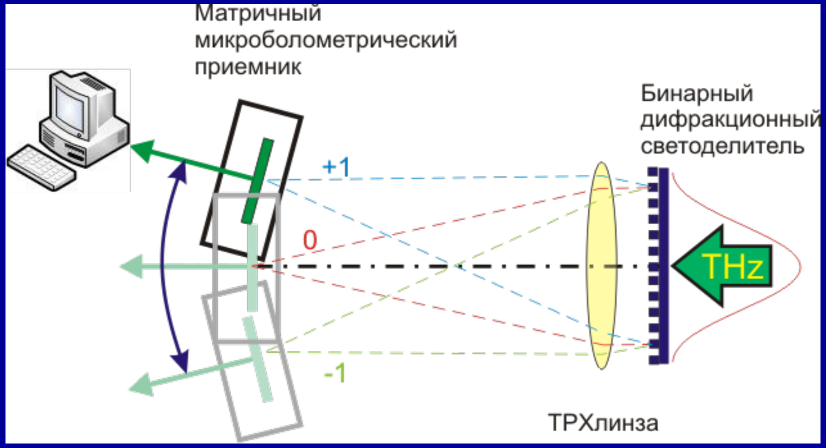
Experimental investigation of DOEs at free electron laser - NovoFEL.

The wavelength λ=141 μm, aperture is 30 mm. Material: high grade silicon HRFZ-Si; polymer (Parilene C) antireflection coating was used. Technology: plasma-chemical etching (Bosch process), working gases: C_4F_8/Ar (passivation) и SF_6/Ar (etching). Maximal etching depth is neatly 30 μm.

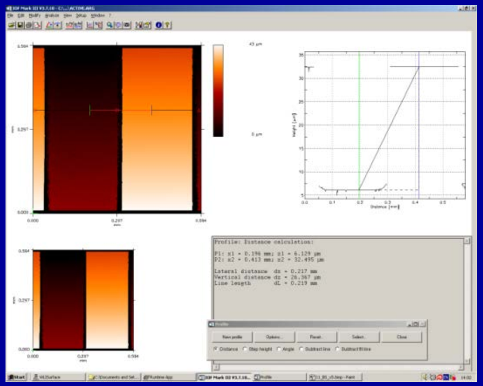
In: Materials of The 2-nd International Conference “Terahertz and Microwave radiation: Generation, Detection and Applications”, p.111, TERA-2012, Moscow, Russia, 20-22 June, 2012.

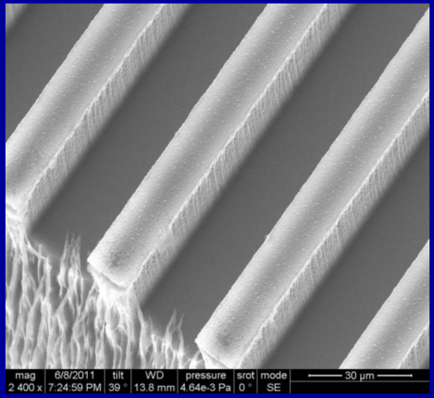
SILICON BINARY DIFFRACTIVE BEAM SPLITTERS OF TERAHERTZ LASERS BEAMS





Experimental investigation of DOEs at free electron laser - NovoFEL.
Estimated diffractive efficiency is 82%.
Measured diffractive efficiency is 79%.

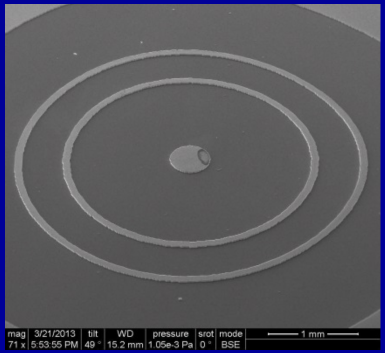




In: Materials of The 2-nd International Conference "Terahertz and Microwave radiation: Generation, Detection and Applications", p.111,
TERA-2012, Moscow, Russia, 20-22 June, 2012.

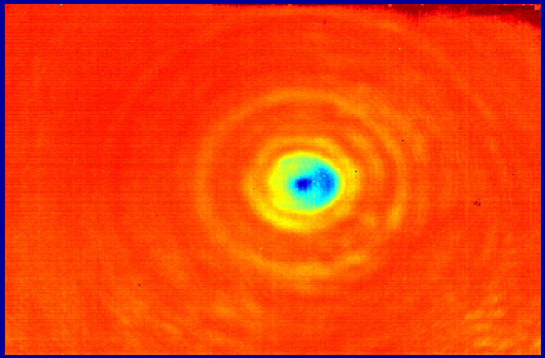
FOCUSING OF POWERFUL THZ BEAM INTO AXIAL LIGHT SEGMENT (ALONGATED FOCUS)

Parameters: aperture – 30 mm, wavelength – 141 μm, distance between element and light segment – 110 mm, radius of gaussian beam – 9 mm, length of axial light segment – 30 mm.
Theoretical estimation of energy efficiency is 19%, experimentally measured efficiency — 18%.



Fragment of microrelief

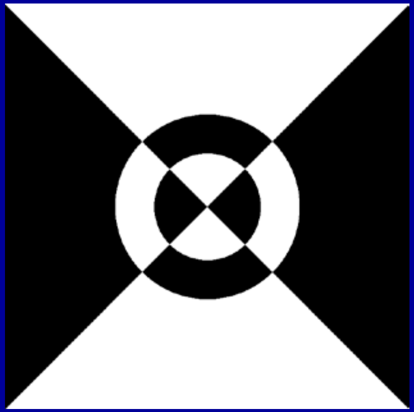
Realised element



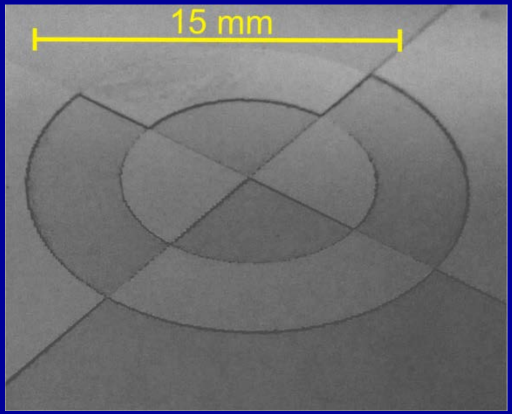
Formed axial intensity distribution, z=90-203 мм

A.N. Agafonov, B.O. Volodkin, D.G. Kachalov, B.A. Knyazev, G.I. Kropotov, K.N. Tukmakov, V.S. Pavelyev, D.I. Tsypishka, Y.Yu. Choporova, A.V. Kaveev Focusing of Novosibirsk Free Electron Laser (NovoFEL) radiation into paraxial segment, *Journal of Modern Optics*, Volume 63, Issue 11, 2016, pages 1051-1054.

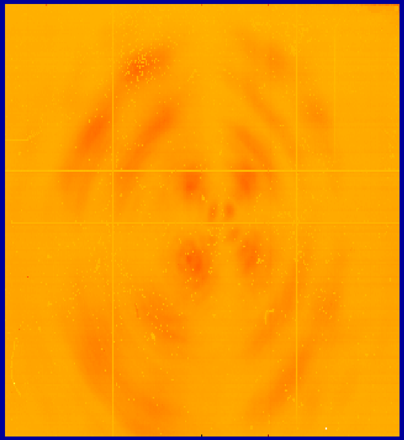
FORMING AND INVESTIGATION OF THZ UNIMODAL LASER BEAMS BY SILICON OPTICAL ELEMENTS



Phase of DOE forming Gaussian-Laguerre mode (2,2)



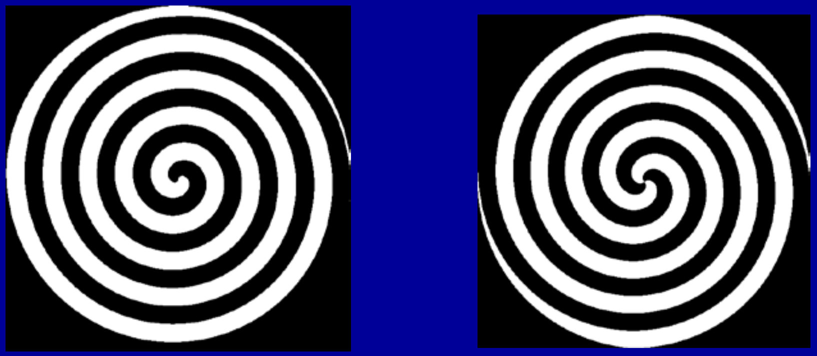
Fragment of realised microrelief



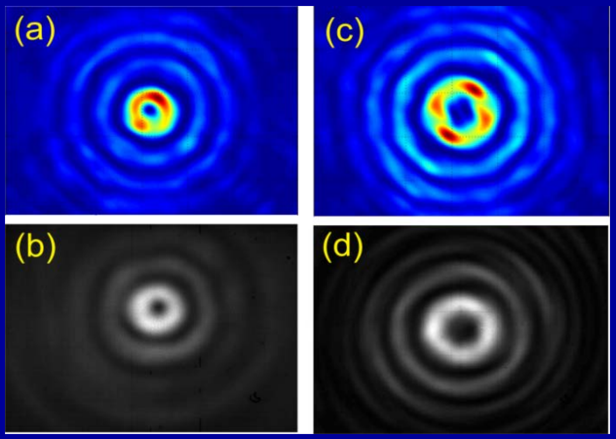
Formed unimodal beam of Thz radiation

A.N. Agafonov, Yu.Yu. Choporova, A.V. Kaveev, B.A. Knyazev, G.I. Kropotov, V.S. Pavelyev, K.N. Tukmakov, B.O. Volodkin Control of transverse mode spectrum of Novosibirsk free electron laser radiation // *Applied Optics*. – 2015 – Vol. 54, N. 12 – 3635-3639.

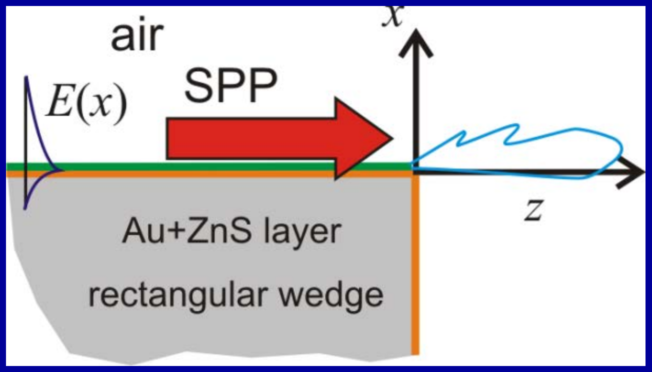
EXCITATION OF THZ PLASMON POLARITONS USING BEAMS WITH ORBITAL ANGULAR MOMENTUM

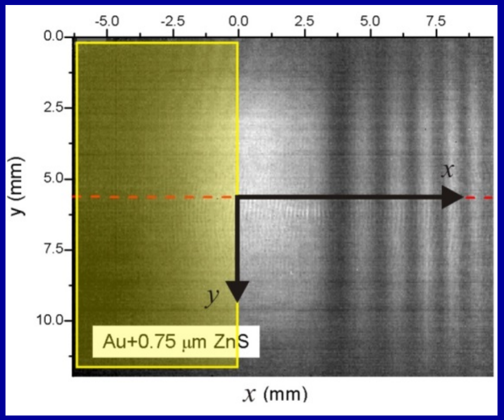


Phase functions of DOEs forming beams with orbital angular momentum $l=\pm1$ (left) и $l=\pm2$ (right)



Calculated (a, c) and measured (b, d) distribution of intensity in cross-section of beams with angular momentum $l = 1$ (a, b) и $l = 2$ (c, d)

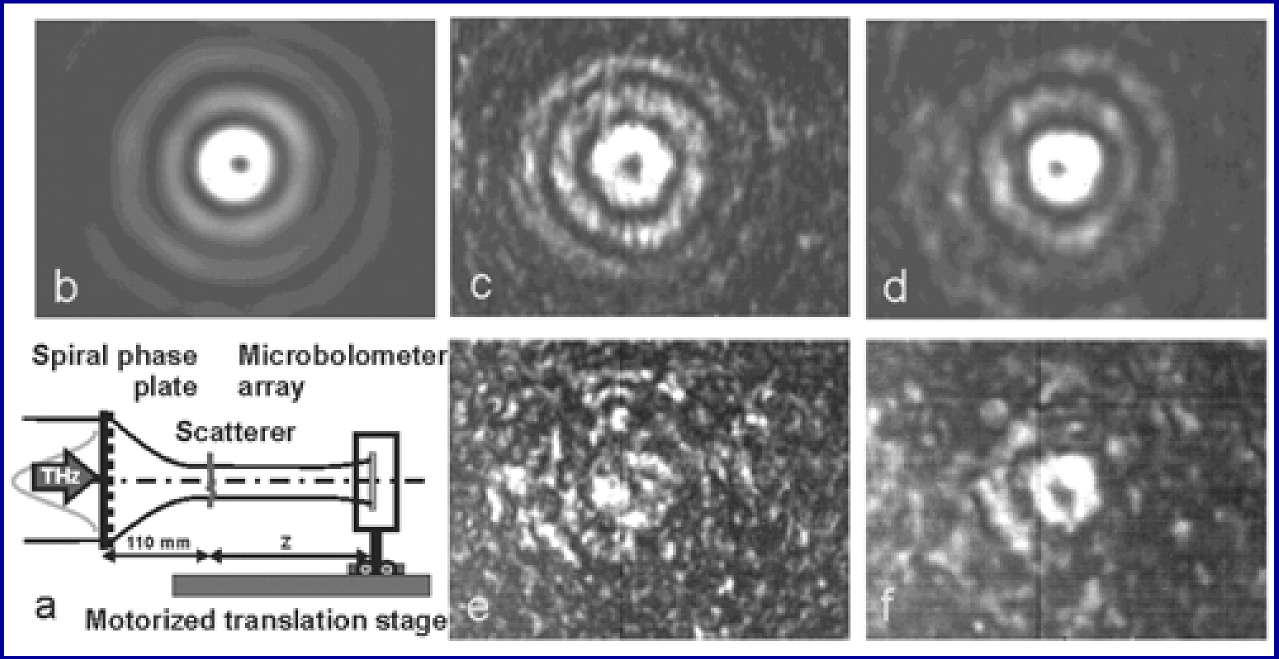




Registratiom of plasmon-polariton by use of diffraction at the waveguide wedge

Generation of Terahertz Surface Plasmon Polaritons Using Nondiffractive Bessel Beams with Orbital Angular Momentum// Yu.Yu. Choporova, M.S. Mitkov, V.S. Pavelyev, B.O. Volodkin/*Phys. Rev. Lett.*- 2015-Vol 115 - 163901.

SELFRECONSTRUCTION OF POWERFUL THZ BEAMS FORMED BY DOES



Selfreconstruction of Bessel beams. (a) Scheme of experiment. (b) Beam cross-section *z*=110 mm. Beam after scatterer (thin film): (c) *Z* = 60 mm, (d) *Z* = 115 mm. Beam after scatterer (thick film) : (e) *Z* = 60 mm, (f) *Z* = 115 mm.

Boris Knyazev; Yulia Choporova; Mikhail Mitkov; Vladimir Pavelyev; Boris Volodkin. High-power terahertz non-diffractive Bessel beams with angular orbital momentum: Generation and application. *40th International Conference on Infrared, Millimeter, and Terahertz Waves*, Hong Kong, 23 - 28 August 2015, art. no. 3129943

DISADVANTAGES OF LITHOGRAPHICAL TECHNOLOGIES

1. «Planar» step-like character of microrelief

2. Realization of multilevel (N>4) microrelief by lithographical technologies is complicated and expansive.

3. Small number of levels restricts the energy efficiency and functionality of optical elements.

FABRICATION OF IR TRANSMISSION OPTICS BY LASER ABLATION

Main problems –

✓Limited diamond plate thickness (till 1.5 mm) and area (100 cm^2)

✓High hardness of diamond plates

Solutions:

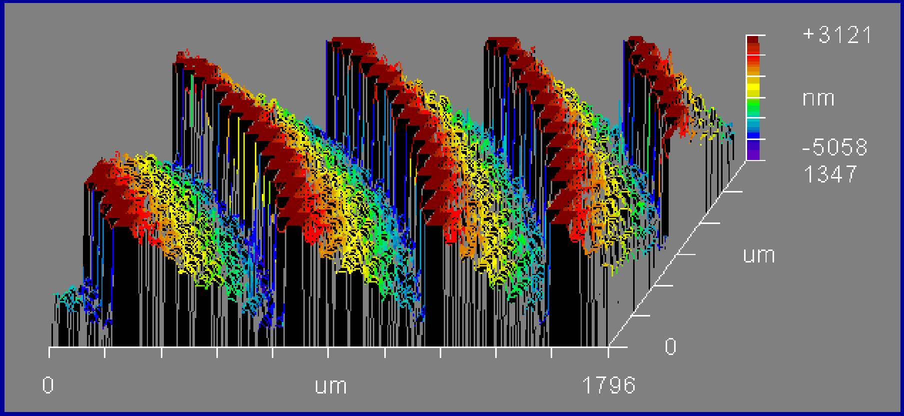
- Diamond Diffractive Optical Elements
- Laser Ablation of Diamond Surface

Polycrystalline CVD diamond film gas-phase synthesis

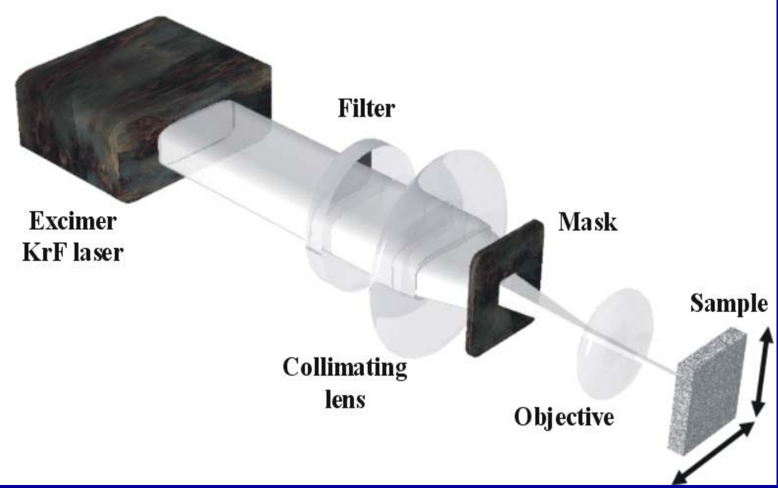
+

Computer design of DOE microrelief

UV-laser structuring of diamond surface



MULTILEVEL DOEs ON DIAMOND FILMS MADE BY UV-LASER ABLATION
(in cooperation with GPI RAS; Moscow)



Material: polycrystalline diamond films
Maximal etching depth is nearly 7.5 mm.

Fabrication

1. The laser patterning of the surface was performed with a KrF excimer
laser (model EMG 1003i “Lambda Physik”, 248 nm wavelength, 15 ns pulse duration, energy per pulse ~200 mJ) in an optical projection scheme with a linear demagnification of 1:10.

2. The graphitised layer has been removed by annealing in the oxygen atmoshere.

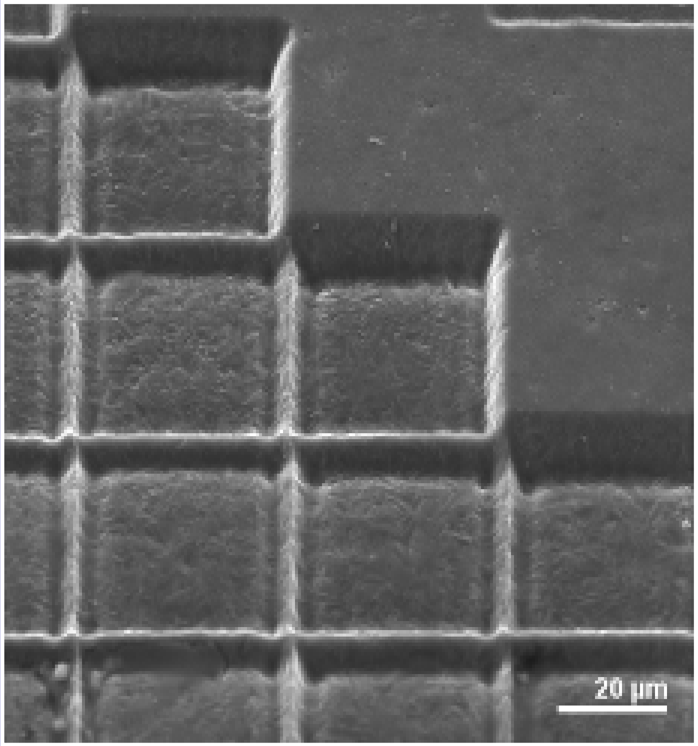
Advantages of technology

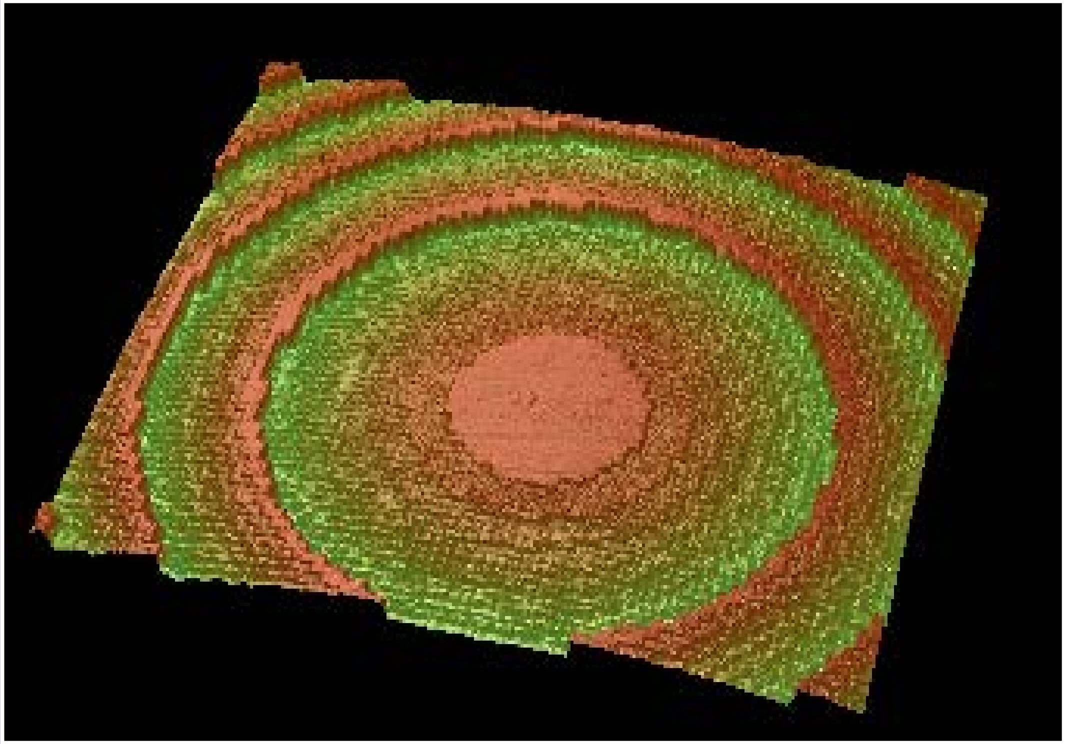
-multilevel structuring,

-relatively small time for producing.

Quantum Electronics, 29 (1) 9-10 (1999)

REALISED MICRORELIEF ON DIAMOND SURFACE
(jointly with GPI of the RAS)

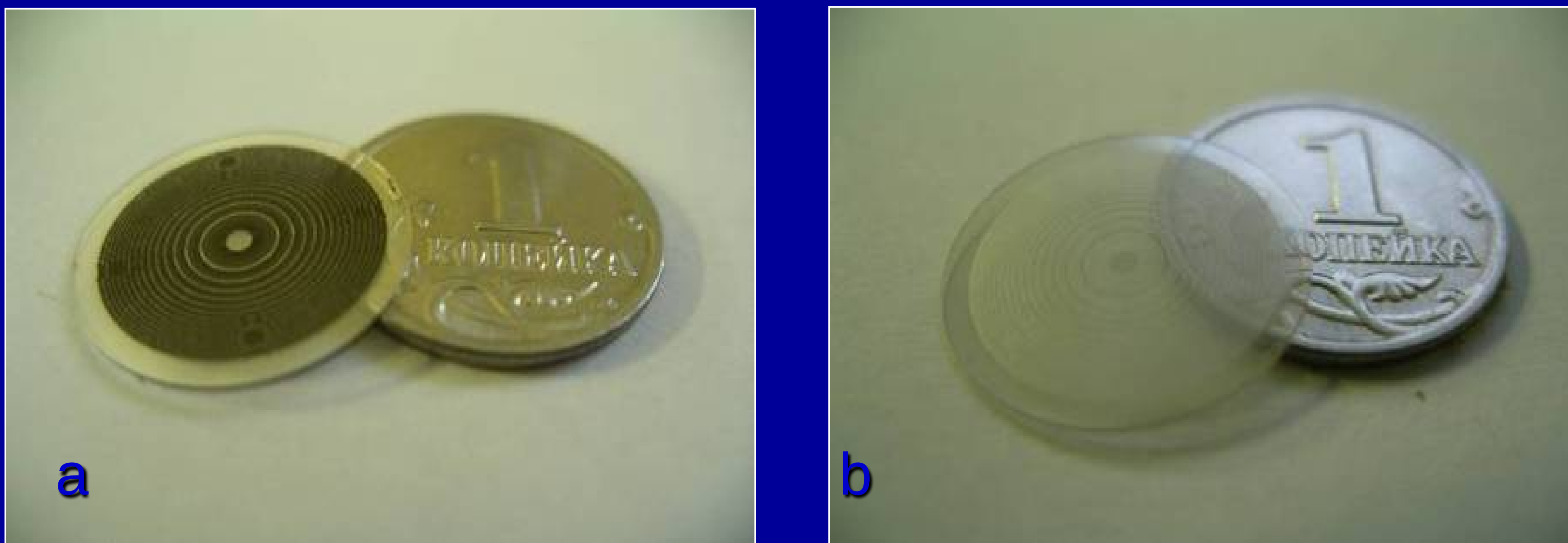




Wavelength: λ = 10.6 µm
Power: 2,1 kW
Energy efficiency: more than 87%
Film thickness: 1 mm
Refractive index: 2.4

Quantum Electronics, 29 (1) 9-10 (1999)

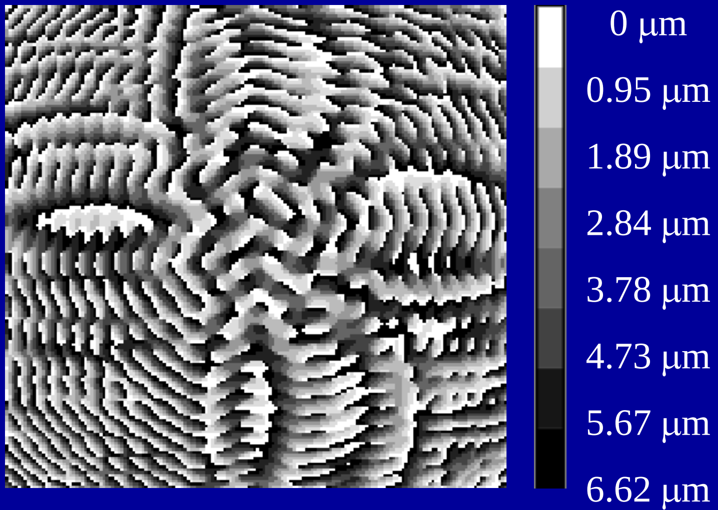
DIAMOND MICROOPTICS FOR CO_2-LASERS

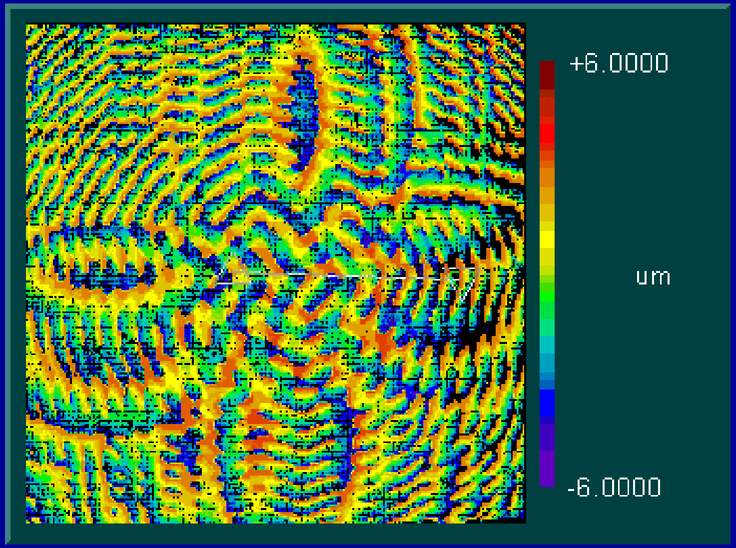


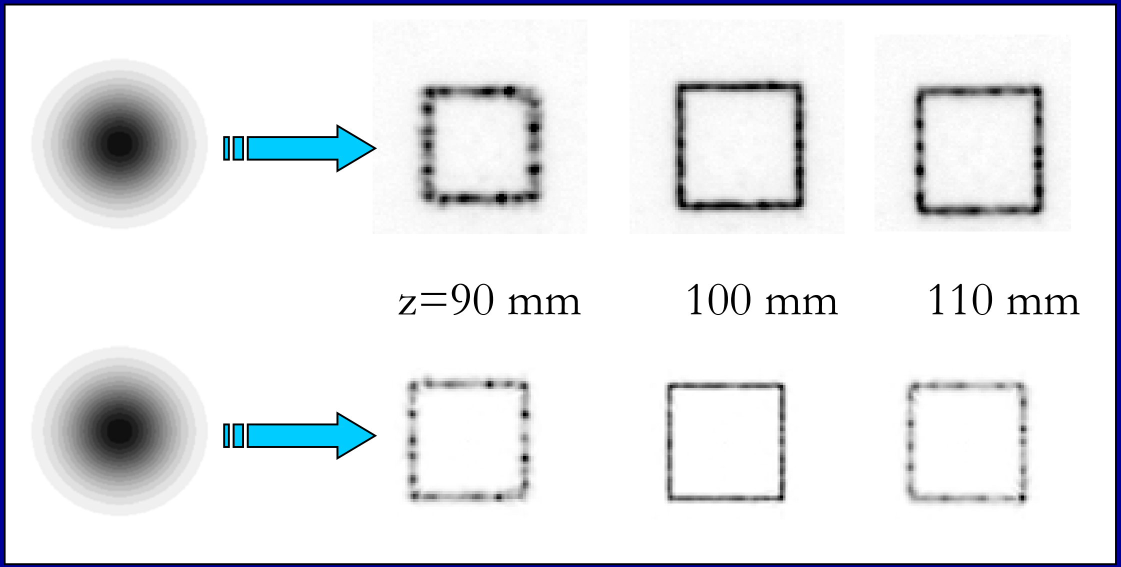
Diamond diffractive lens before (a) and after (b) removing of graphite

V. S. Pavelyev, V. A. Soifer, V. I. Konov et al. in: High-Power and Femtosecond Lasers, Editor: Paul-Henri Barret and Michael Palmer, 2009, Nova Science Publishers, Inc.

FOCUSING OF CO_2-LASER BEAM INTO SQUARE CONTOUR

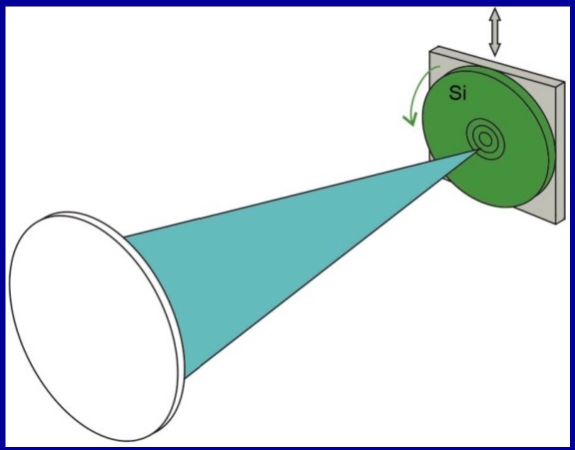
a)


b)


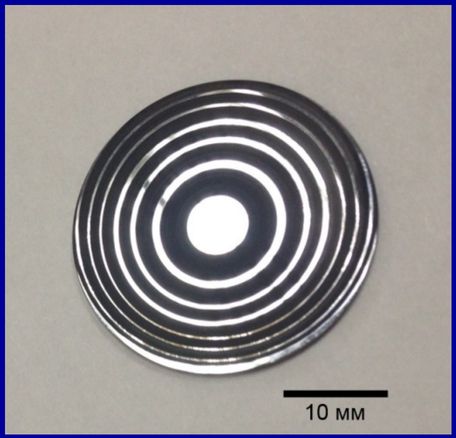
c)


(a) calculated microrelief;
(b) DOE microrelief;
(c) CO_2 laser Intensity distribution in the focal plane: experiment (up) vs computer simulation (down).

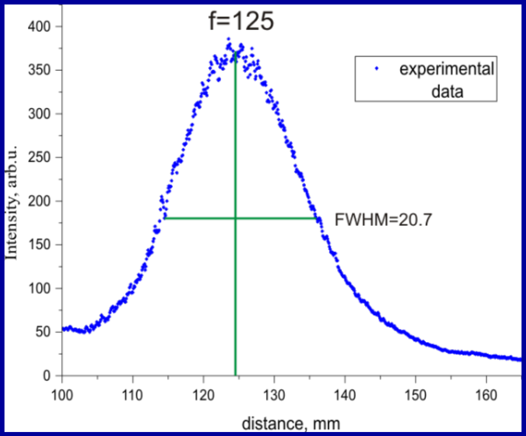
FABRICATION OF HIGH-EFFICIENT POWER THZ OPTICS ON THE BASE OF LASER ABLATION OF SILICON SURFACE



Scheme of laser ablation (λ = 1030 nm, τ = 400 fs, f = 200 kHz, Yb:YAG laser) of silicon plate



Fabricated 4-level diffractive lens

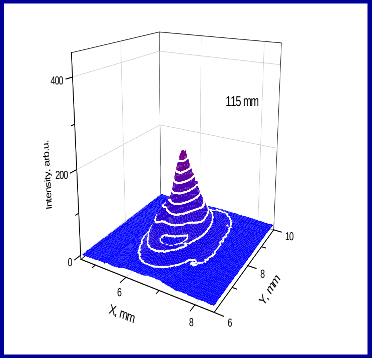


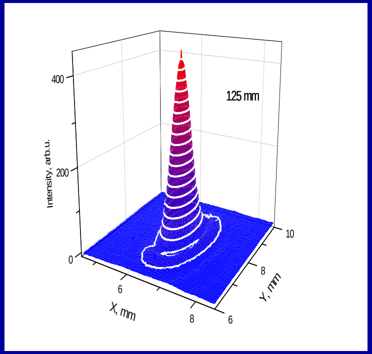
Measured intensity distribution along optical axis

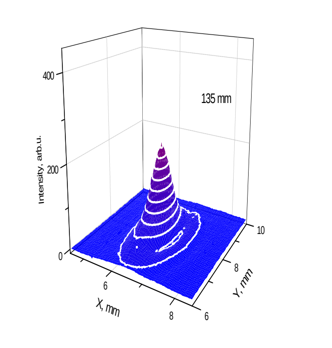
Measured efficiency is in good agreement with calculated estimation (λ=141 μm).

M.S. Komlenok, B.O. Volodkin, B.A. Knyazev, V.V. Kononenko, T.V. Kononenko, V.I. Konov, V.S. Pavelyev, V.A. Soifer, K.N. Tukmakov, Yu.Yu. Choporova, Fabrication of a multilevel THz Fresnel lens by femtosecond laser ablation, *Quantum Electronics*, 2015, 45 (10), 933–936

INVESTIGATION OF FABRICATED SILICON LENS







3D intensity distribution at different distances from fabricated lens (focal distance is 125 mm)

a) 115 mm, b) 125 mm, c) 135 mm

Measured energy efficiency is 75% (theoretical estimation – 81%)

M.S. Komlenok, B.O. Volodkin, B.A. Knyazev, V.V. Kononenko, T.V. Kononenko, V.I. Konov, V.S. Pavelyev, V.A. Soifer, K.N. Tukmakov, Yu.Yu. Choporova, Fabrication of a multilevel THz Fresnel lens by femtosecond laser ablation, *Quantum Electronics*, 2015, 45 (10), 933–936

CONCLUSIONS

Further improvement of developed technology (incl. increasing the number of levels) will lead to appearing of new optical elements of terahertz range with high energy efficiency and advanced functional capabilities.

REFLECTIVE "FREE-FORM" ELEMENTS FOR THZ LASER BEAM CONTROL

3-D printing + vacuum deposition of copper layer

Fabricated in REC of Nanotechnology, Samara University

ACKNOWLEDGEMENTS

This work was supported by Ministry of Education and Science of RF (project 1879) and by grant RSF № 14-22-00243.