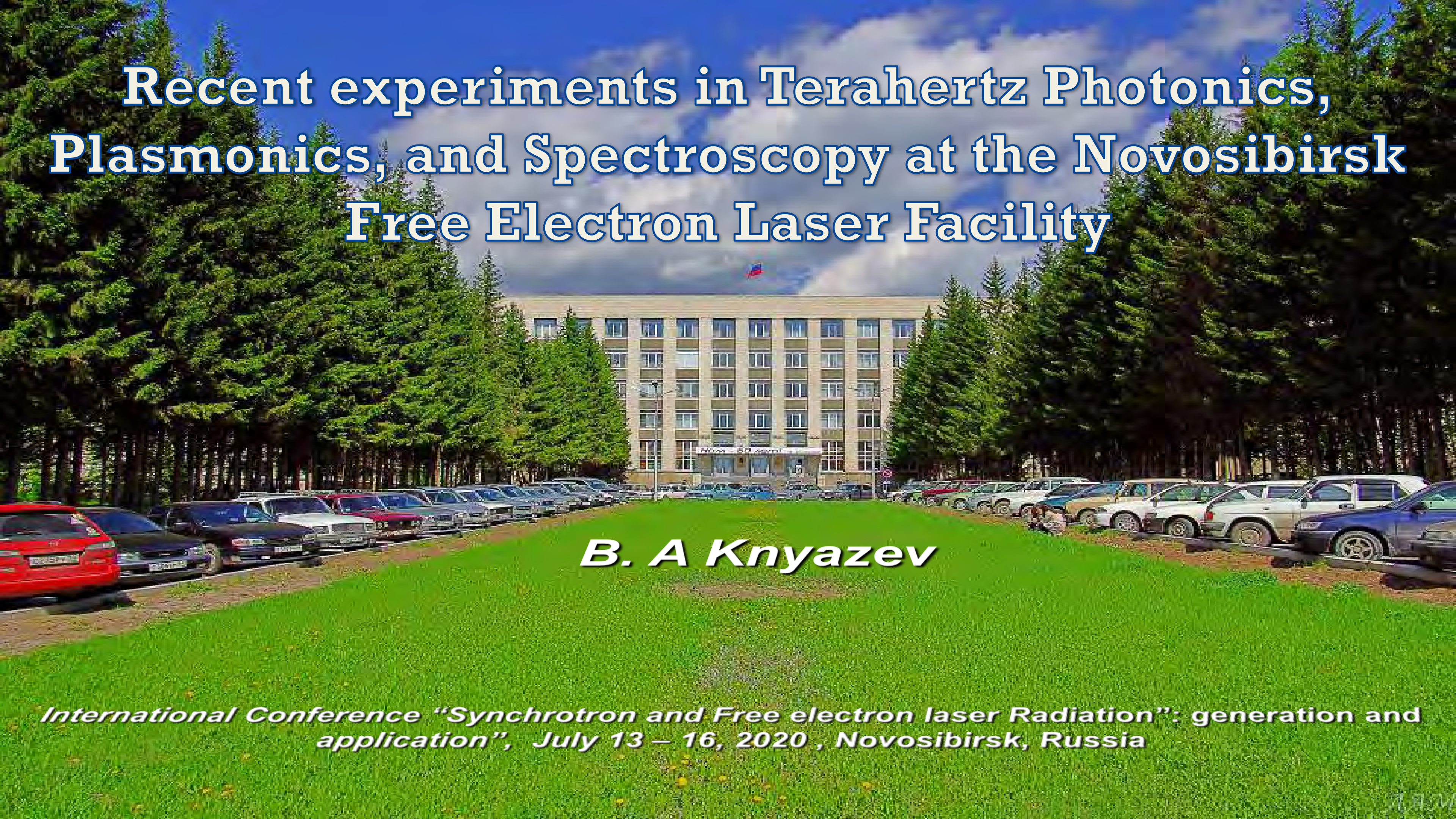
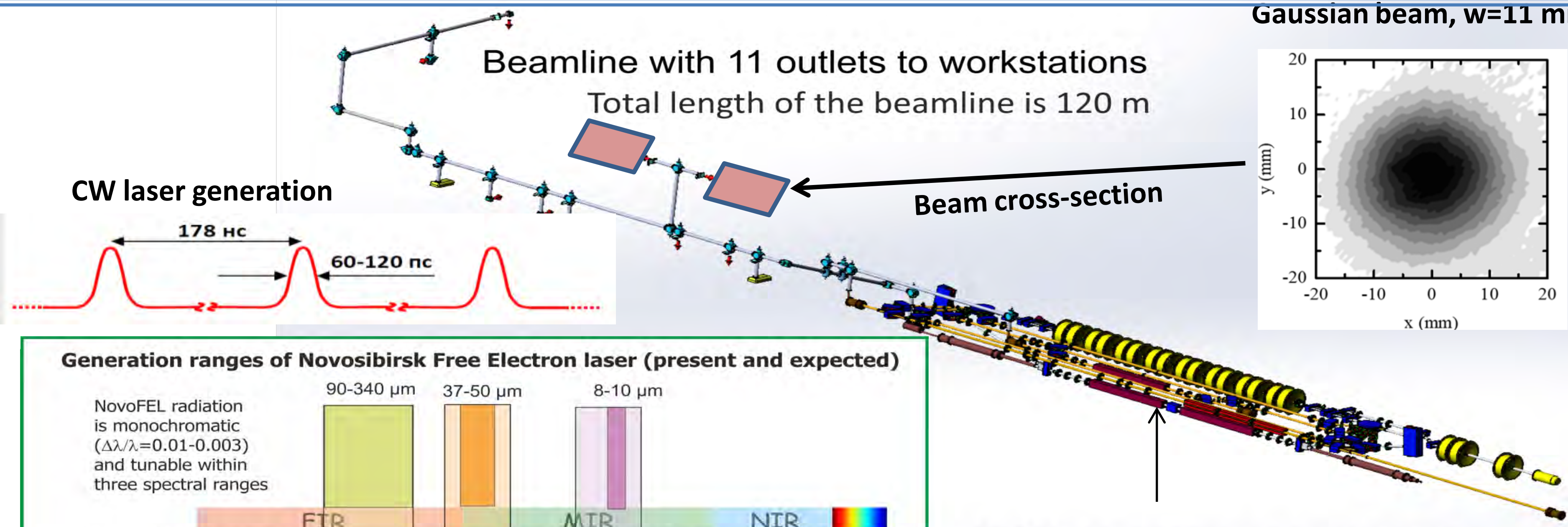


Recent experiments in Terahertz Photonics, Plasmonics, and Spectroscopy at the Novosibirsk Free Electron Laser Facility

B. A Knyazev

International Conference "Synchrotron and Free electron laser Radiation": generation and application", July 13 – 16, 2020 , Novosibirsk, Russia

NovoFEL and user stations



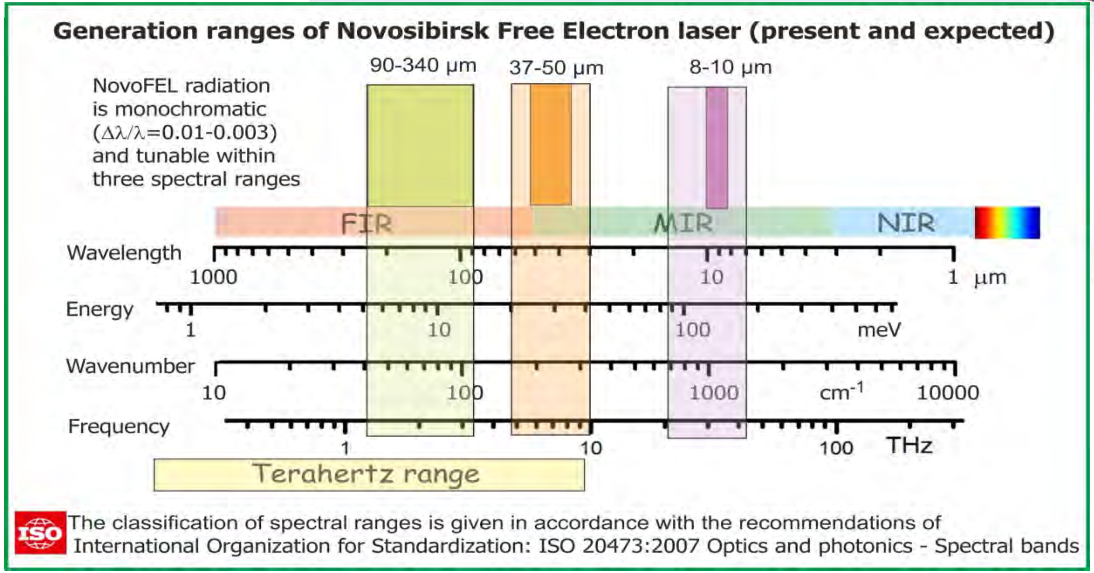
Beamline with 11 outlets to workstations

Total length of the beamline is 120 m

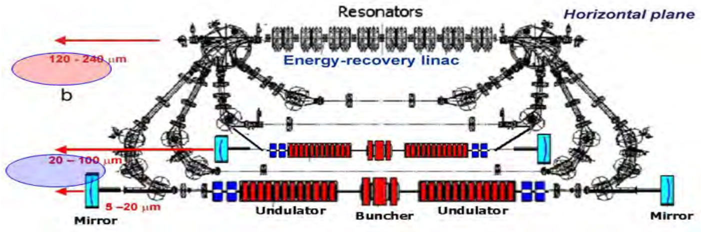
Beam cross-section

Gaussian beam, w=11 mm

CW laser generation

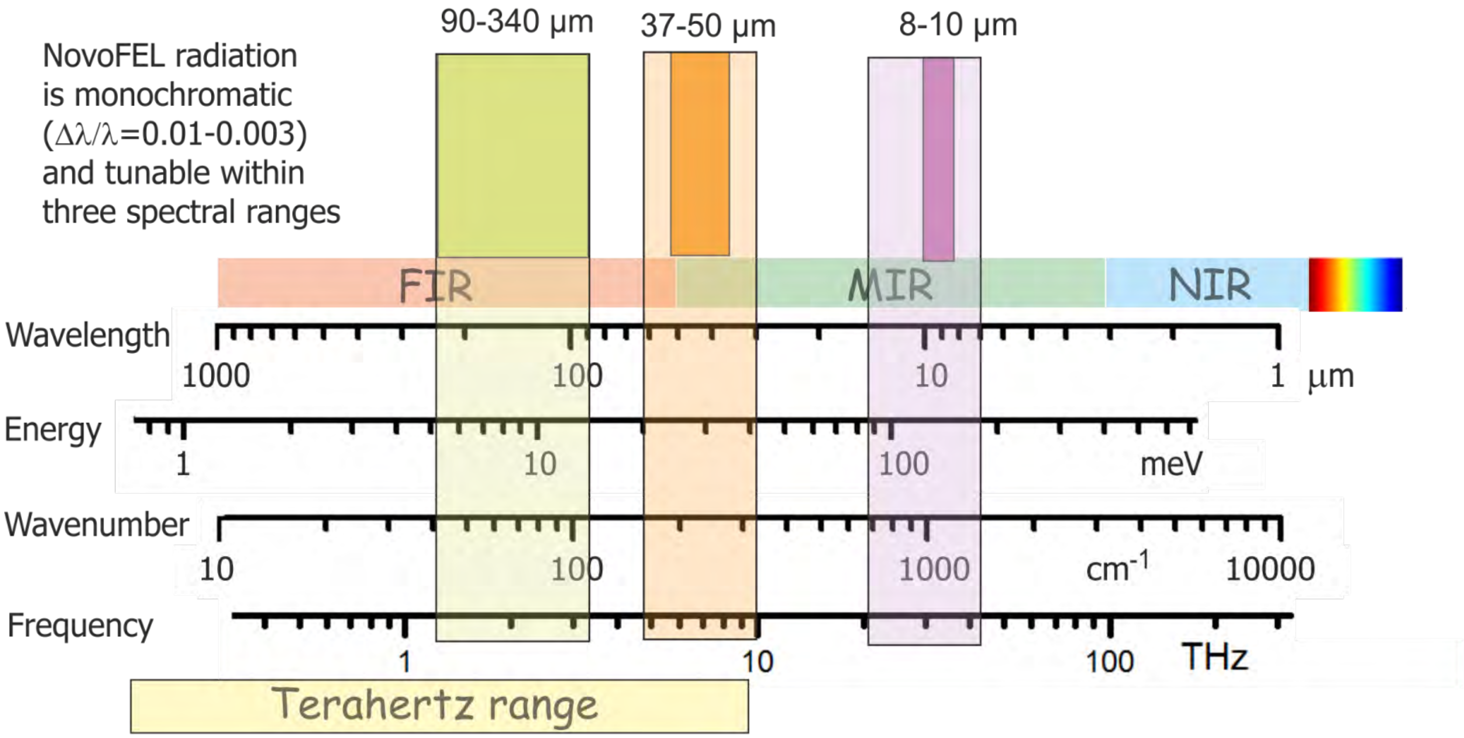


Multiturn energy recovery linac with three individual laser systems



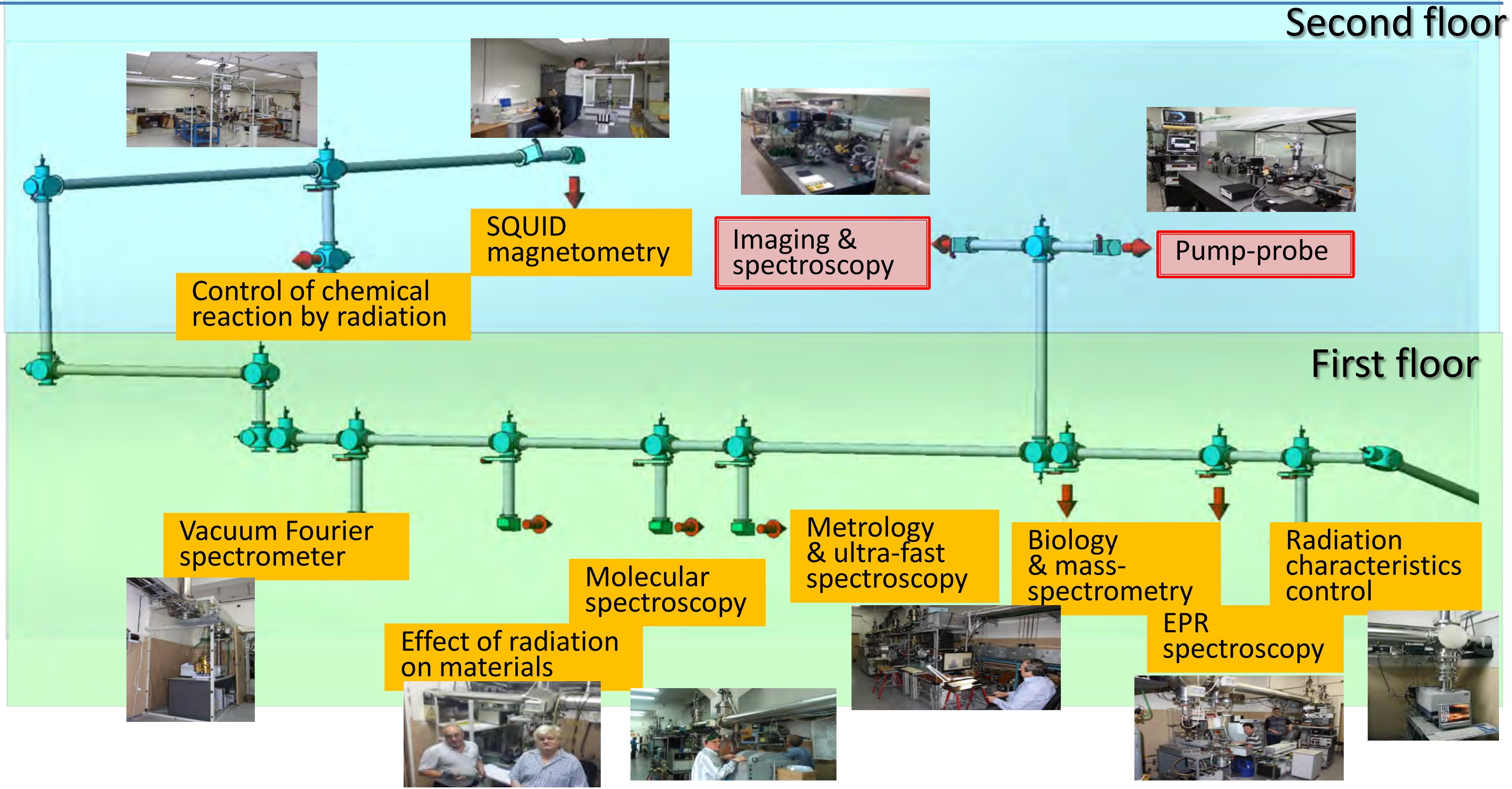
NovoFEL / Generation ranges

Generation ranges of Novosibirsk Free Electron laser (present and expected)

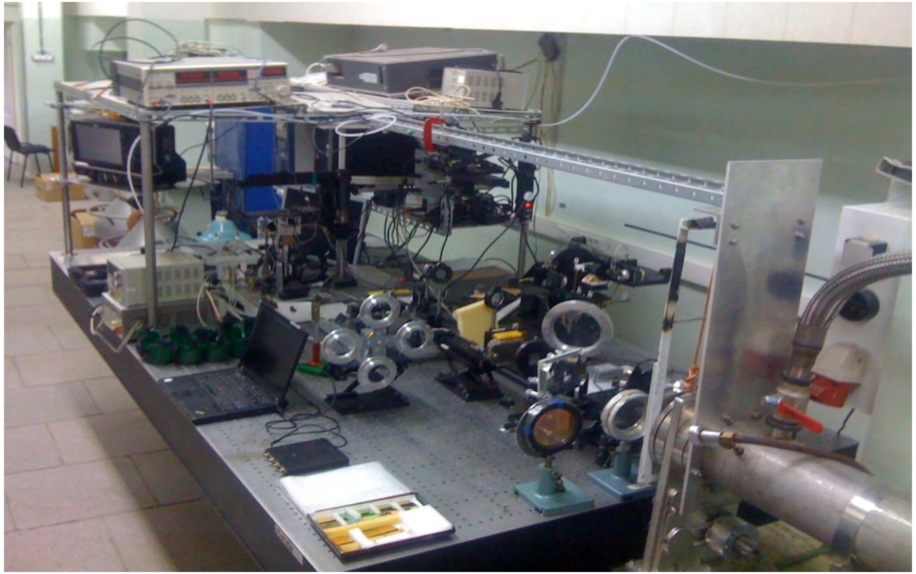


The classification of spectral ranges is given in accordance with the recommendations of International Organization for Standardization: ISO 20473:2007 Optics and photonics - Spectral bands

User stations / Experiments on two workstations will be described



User stations



Station for Imaging & spectroscopy

Pump-probe station

Outline / List of experiments

Photonics

Control and transformation of terahertz beams

- Diffractive optical elements (DOE)
  - Binary
  - Multilevel
  - Free-form
- Vector beams
  - Vector beams
  - Vector vortex beams
  - Mixed vortex beams
- Lattices of vortex beams
- Acousto-optics

Plasmonics

Terahertz surface waves

- SPP quasi-optics
  - SPP on curved surface
  - Surface sensing
  - Plasmonic radar
- Vortex SPPs

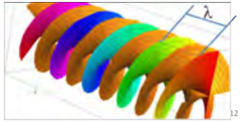
Spectroscopy

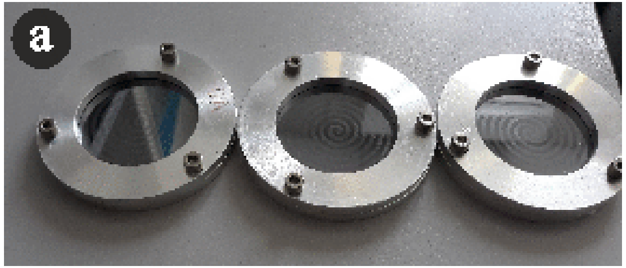
Semiconductor spectra

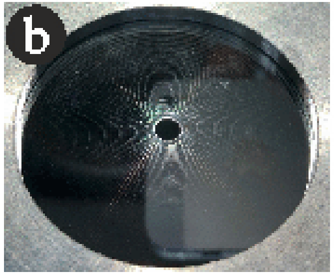
- Pamp-probe experiments
  - Ge-Sb
  - Ge-As

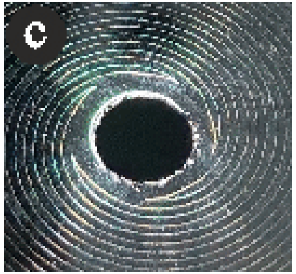
Diffractive optical elements / Binary  $0 \leftrightarrow \pi$

- ❑ Advantages
  - Ease of manufacture
  - DOEs with no zero diffraction order
  - Capability forming sophisticated focal volumes
  - Possibility working at shifted wavelength
  - Low absorbtion
- ❑ Drawbacks
  - Low diffraction efficiency

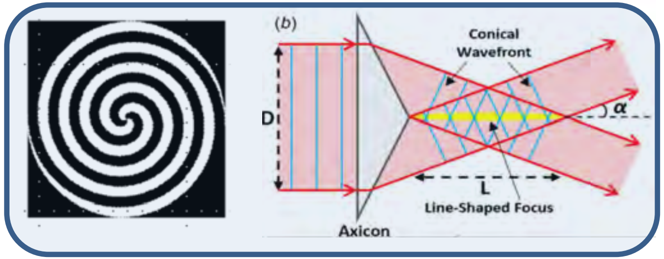


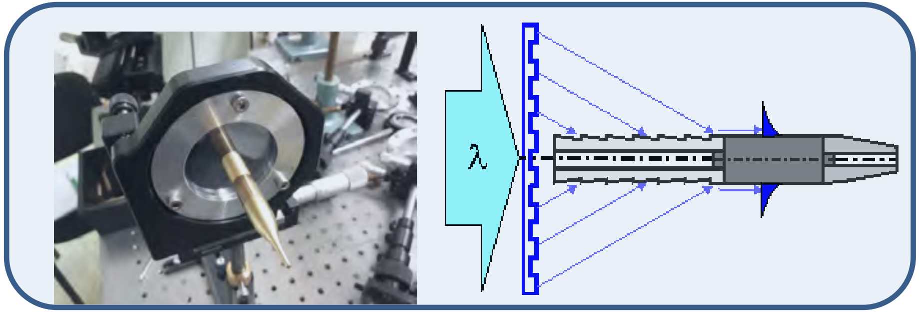






Spiral binary diffraction gratings and there application:
- o **Generation of vortex beams**
- o **Excitation of surface plasmons**

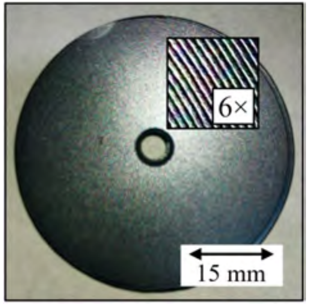




Diffractive optical elements / Binary /

(a) (b) (c)

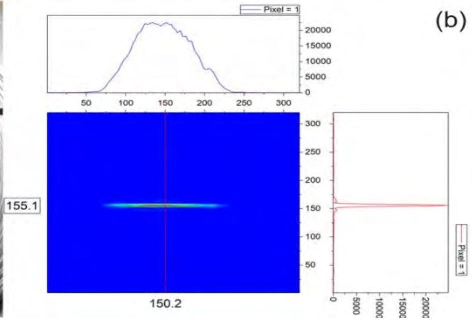
Silicon binary phase axicon for the formation Bessel beam of the first kind of a third-order. The diameter of the element is 100 mm, the relief depth is 29 mm. The photoresist was not completely removed, but the quality of the Bessel beam nevertheless seems acceptable.



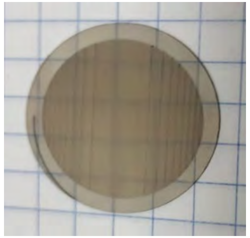
A large wavelength of radiation in the terahertz range gives additional advantages for the DOE production technology.
On one hand, it makes it easy to manufacture DOEs whose structural elements are less than the wavelength.
On the other hand, the terahertz range is convenient for experimental modeling of wavelength DOEs developed for the visible range.

A. N. Agafonov et al., Journal of Modern Optics 63, 1051-1054

Diffractive optical elements / Multilevel

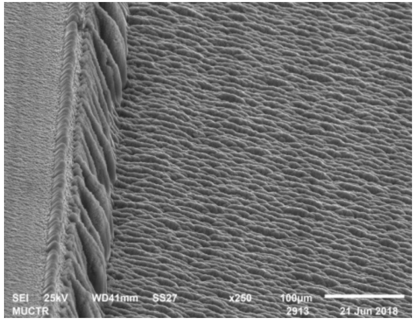


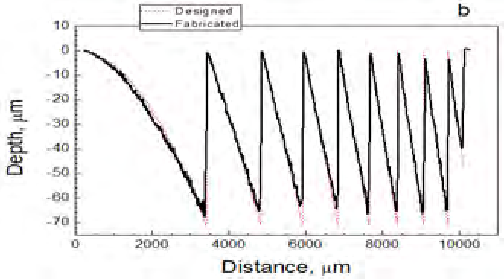
- ❑ Anvantages
  - High diffractive efficiency
  - Capability forming sophisticated focal volum
  - Low absorbtion
- ❑ Drawbacks
  - Works at a determined wavelength
  - Complexity of manufacturing
  - High manufacturing cost
- ❑ Materials
  - Plastics
  - High-resistivity silicon
  - Diamond



Formation of multilevel microrelief requires an expensive and complex procedure of a photomask alignment. New approach to fabricate multilevel silicon DOEs applying femtosecond laser ablation has been proposed recently

Prokhorov General Physics Institute: Optimization of laser ablation processing. 1 ps laser pulses at λ=1.03 µm allows formation of cylindrical Fresnel lens with the surface roughness of 0.5 - 1.2 µm being one order of magnitude smaller than reported earlier

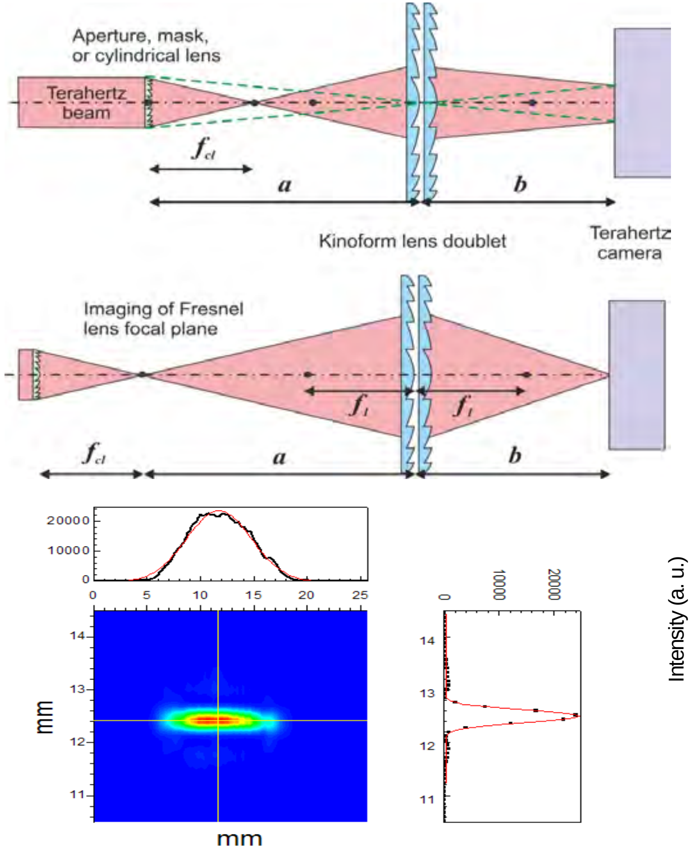




B.O. Volodkin, Quantum Electronics **45**, 933 (2015).

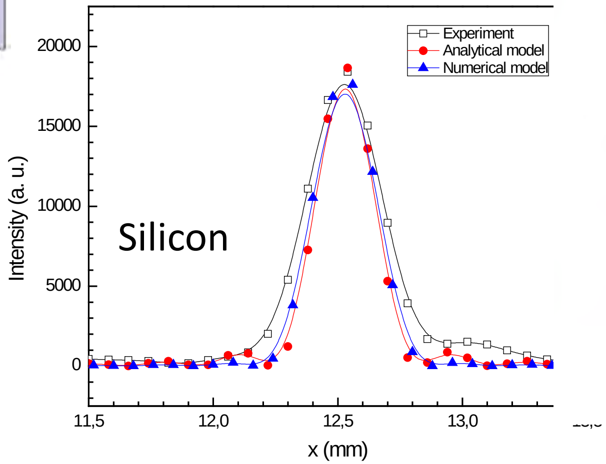
T.V. Konontnko, et al., Optics & Laser Technology **123**, 105953

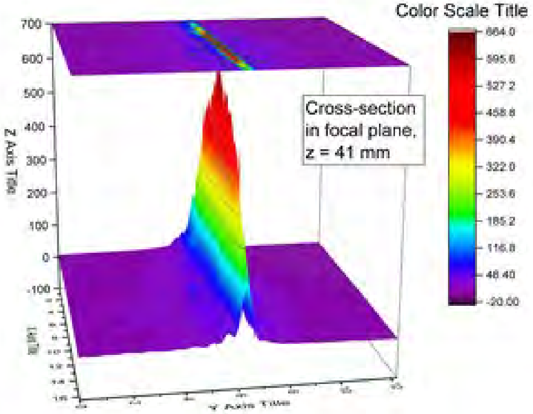
Diffractive optical elements / Multilevel



Study silicon lens performance

- ❑Imaging device Pyrocam IV (25x25 mm^2)
- ❑ Projective imaging system
- ❑ Polypropylene Fresnel lens doublet (2x D80 mm, F80 mm)
- ❑ Si lens diameter 20 mm, focus 41±1 mm (calc. 40 mm)
- ❑ Roughness 0.5 – 1.2 μm
- ❑ Half-width 0.35 mm





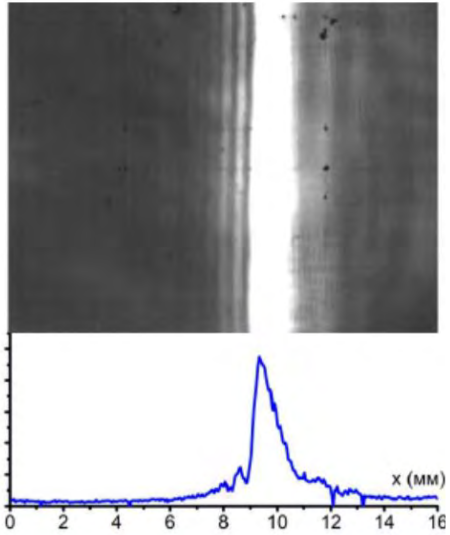
Diamond

Diffractive optical elements / Free-form

At the Department of Nanotechnology, Samara University, calculation methods and microprocessing technology are being developed for the manufacture of reflective diffraction elements with an arbitrary surface shape. Such mirrors are ideal for powerful sources of terahertz radiation, such as FEL and gyrotron, and have high diffraction efficiency.

Photo of a 45-degree reflecting cylindrical mirror made of aluminum by milling and a focal spot recorded with a microbolometer array at a wavelength of 129.5 µm. Measured diffraction efficiency was 94%.

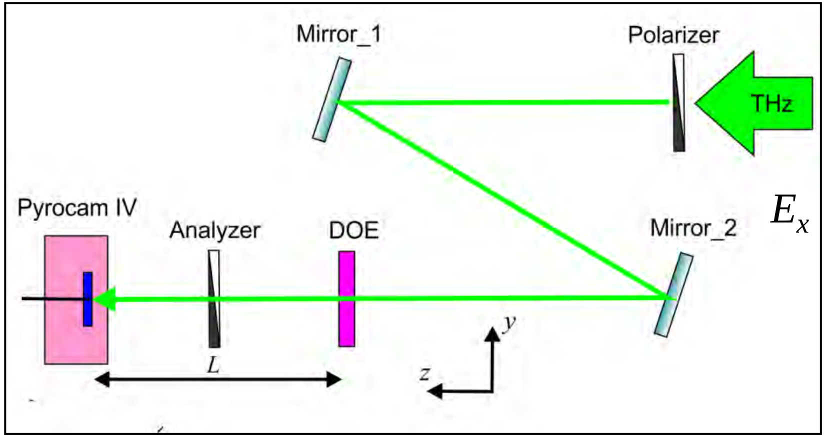
(a)

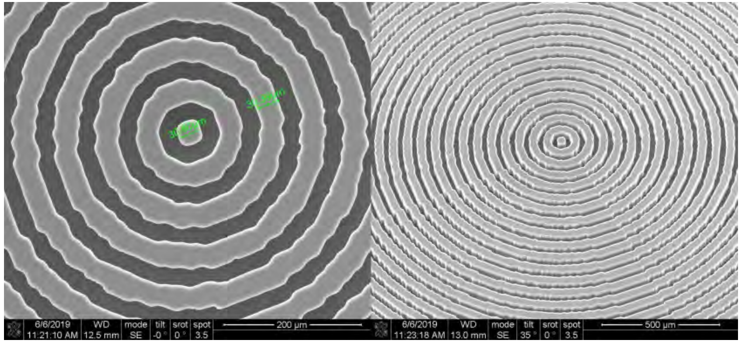


(b)

V. S. Pavelyev, et al,'' In EPJ Web of Conferences 2018 (Vol. 195, p.

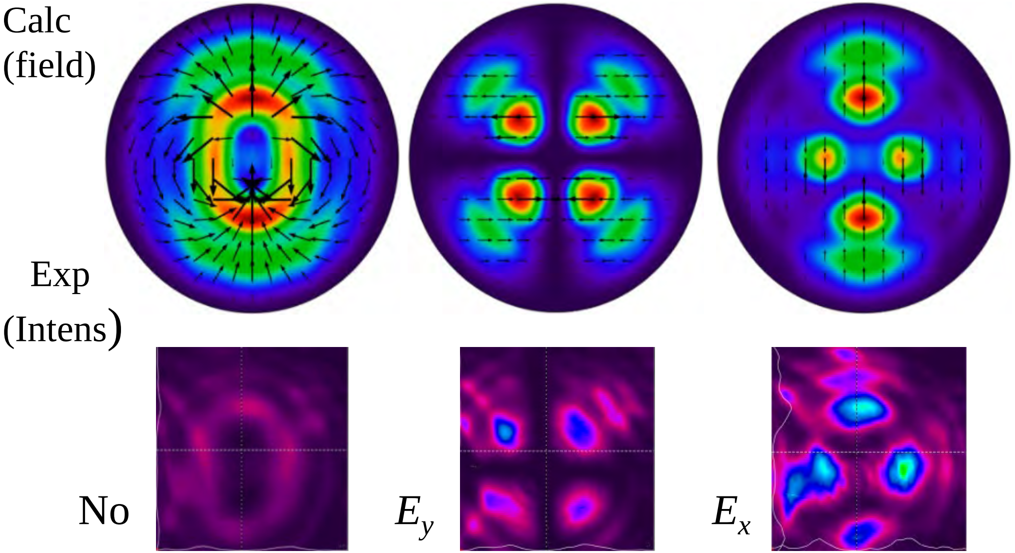
Vector beams / Subwavelength DOE for vector beam formation





Period p = 60 μm), h = 50 μm, λ^* = 129 μm

Gaussian beam (w = 11 mm), λ = 128,7 μm, E_x



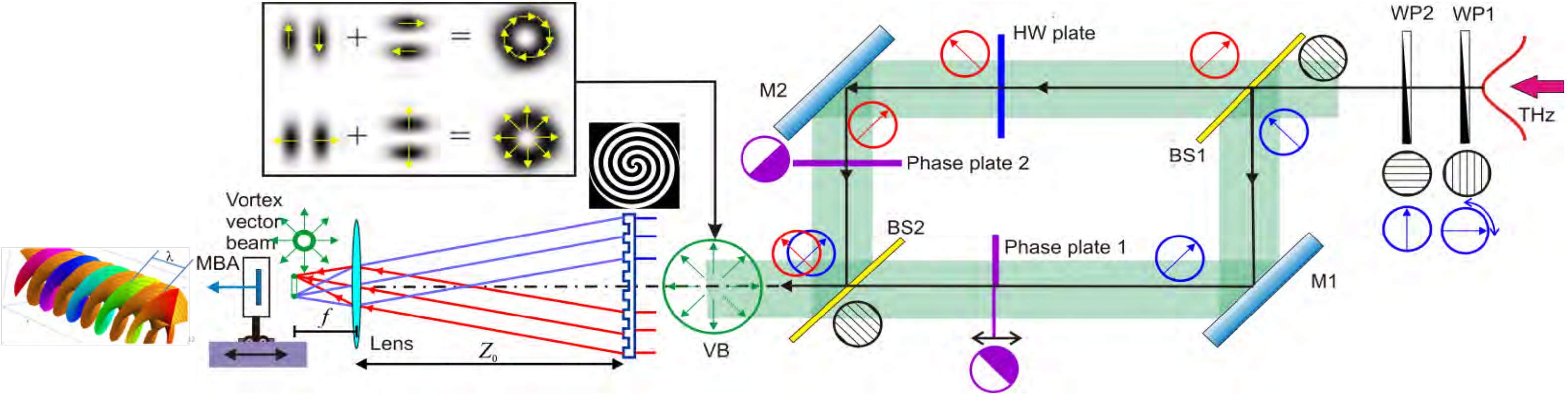
Different analyzer orientation

$\lambda = 129$ μm

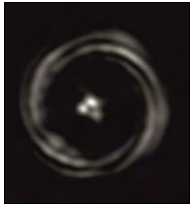
S.N. Khonina, et al., Computer optics, V.43, No. 5,

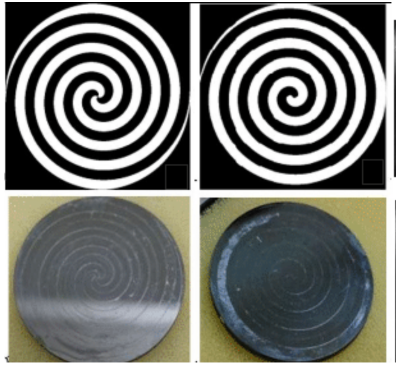
12

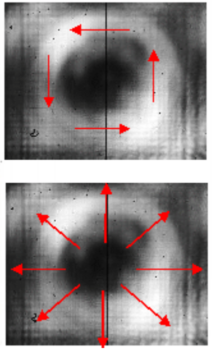
Vector beams / Vector vortex beams / Perfect vector beams



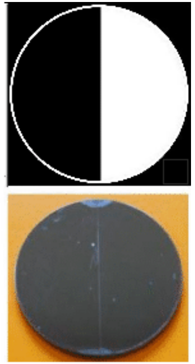
Perfect vector vortex beam ← Vector vortex beam ← Vector beam ← Gaussian beam



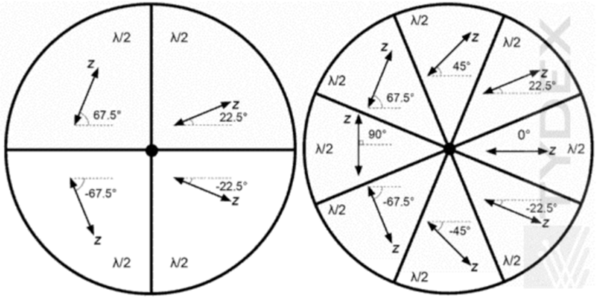




Spiral axicons



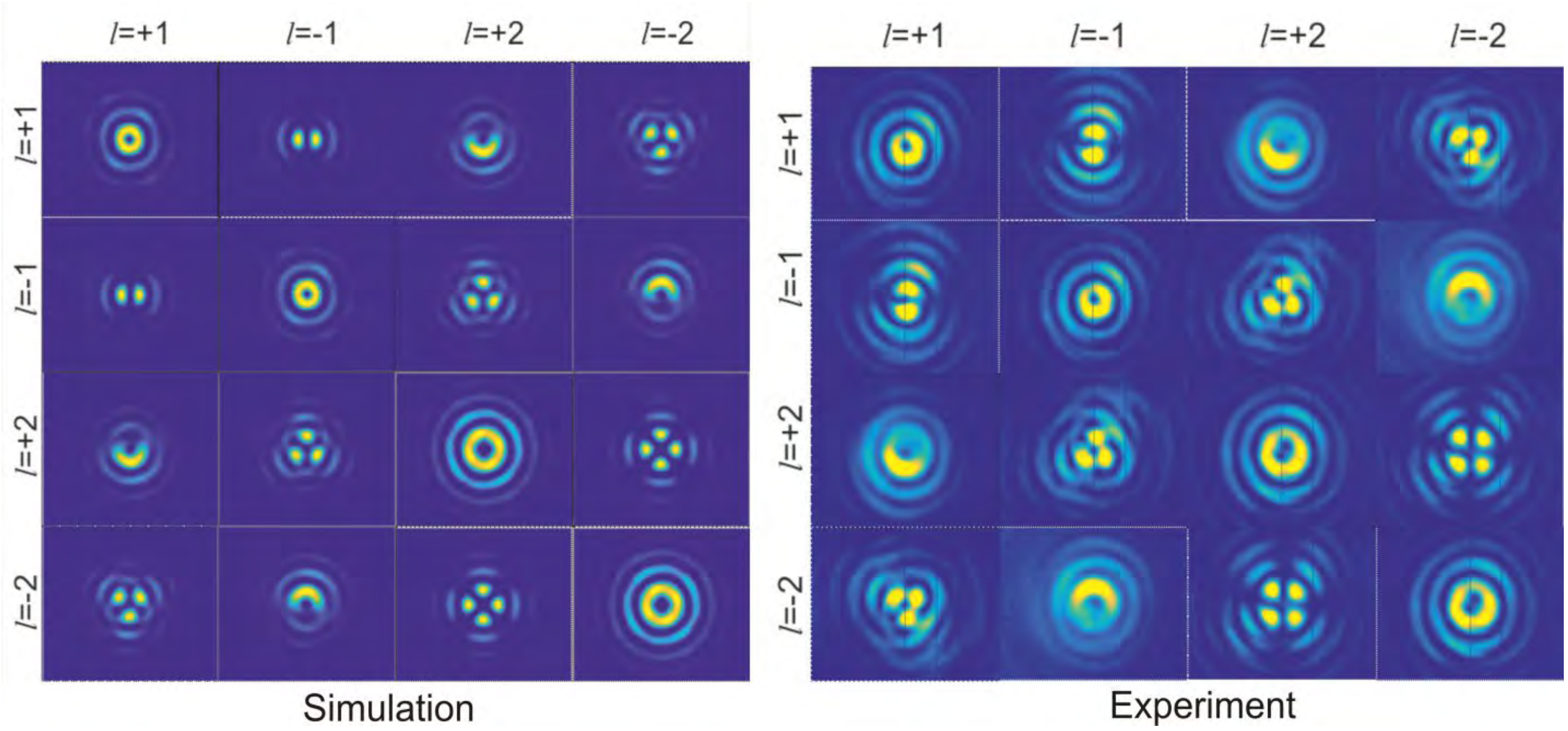
HG Phase plate



Segmental wave plate

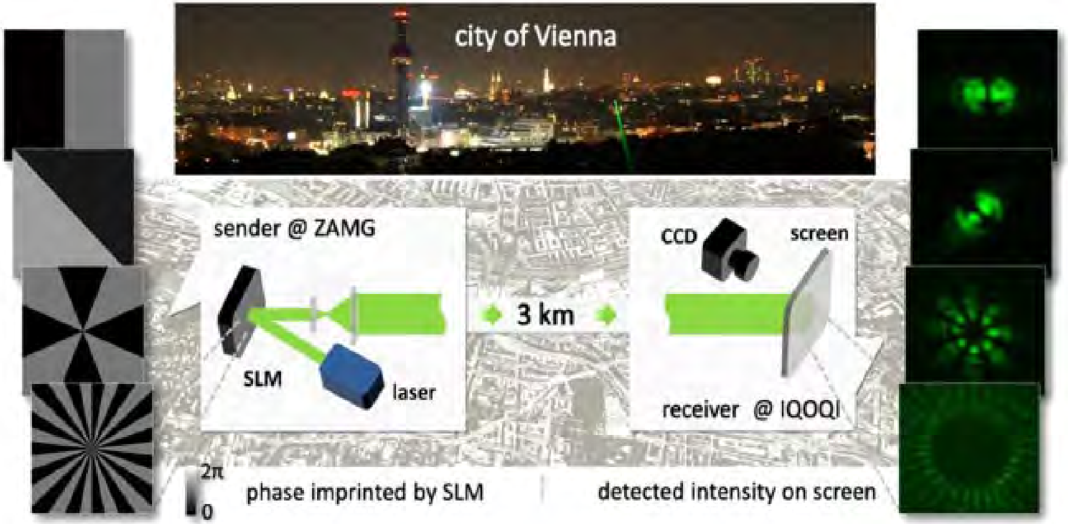
Y. Y. Choporova, et al., IRMMW-THz, Париж

Vector beams / Mixed vortex beams



Y. Y. Choporova, et al., IRMMW-THz, Париж

Optical communications using OAM multiplexing



Krenn et al., New J. Phys. 16, 1367 (2014)

Vortex beam orthogonality

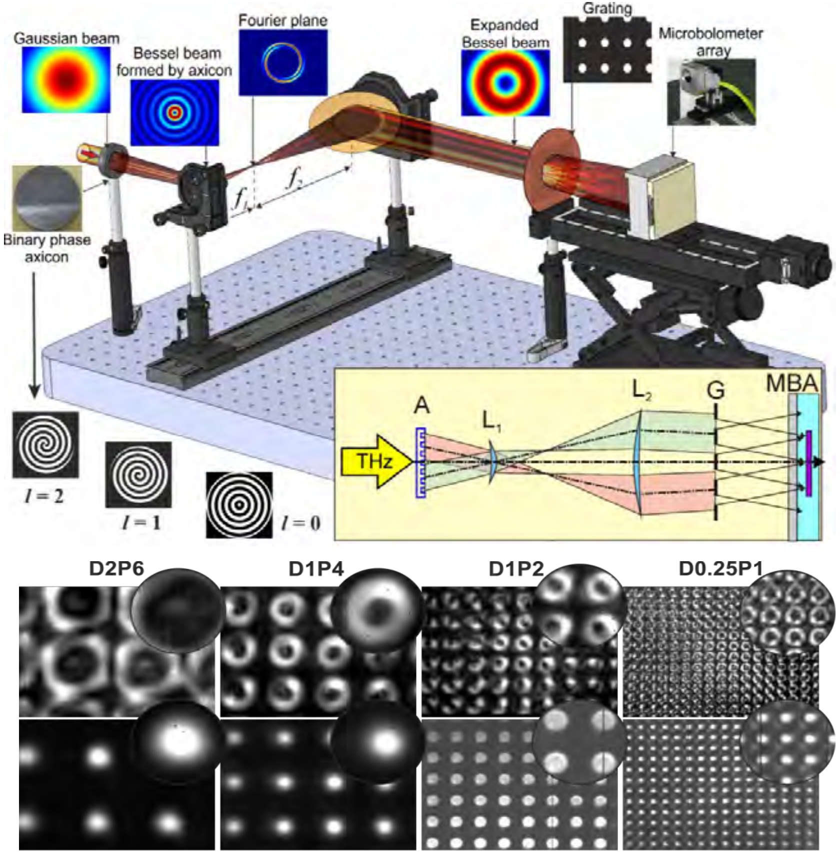
$$\int_0^{2\pi} U_1 U_2^* \, d\theta = \begin{cases} 0 & \text{if } \ell_1 \neq \ell_2 \\ A_1 A_2^* & \text{if } \ell_1 = \ell_2 \end{cases}$$

Types of communications using vortex beams

- ❑ Free space communication
- ❑ Optical fiber communication
- ❑ Plasmonic waveguide for communication in the terahertz range ?

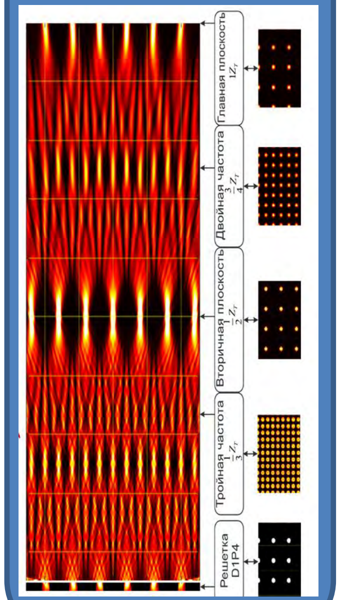
(see below)

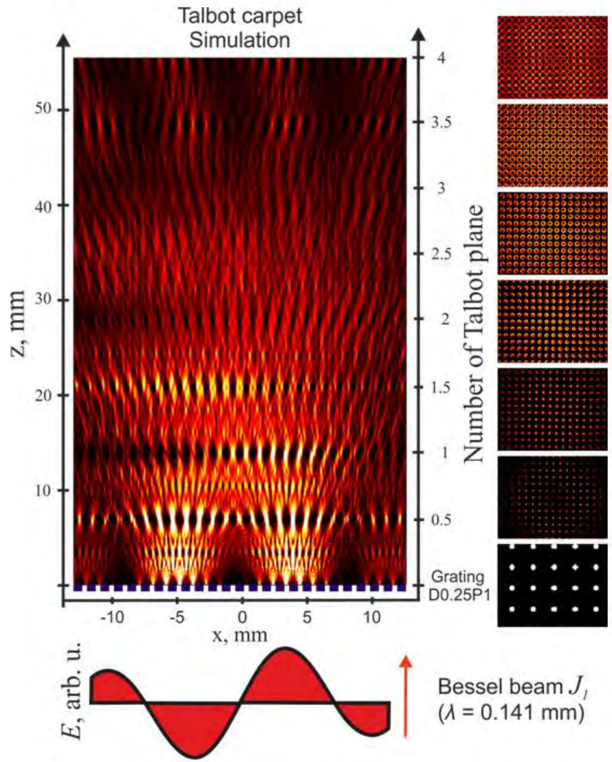
Generation of lattices of vortex microbeams



Experiment, λ = 0.141 mm Talbot plane numbers ($z/L_T = j + v/u$)

Classical Talbot carpet





I.A. Kotelnikov, et al., Journal of Optics **22**, 065603

Acousto-optical effect in liquefied SF_6

First experiments on acousto-optical effect in non-polar liquefied gas were carried out at NovoFEL. . The value of the diffraction efficiency obtained in liquefied sulfur hexafluoride appears to be 100 times higher than in the best non-polar liquid hexane.

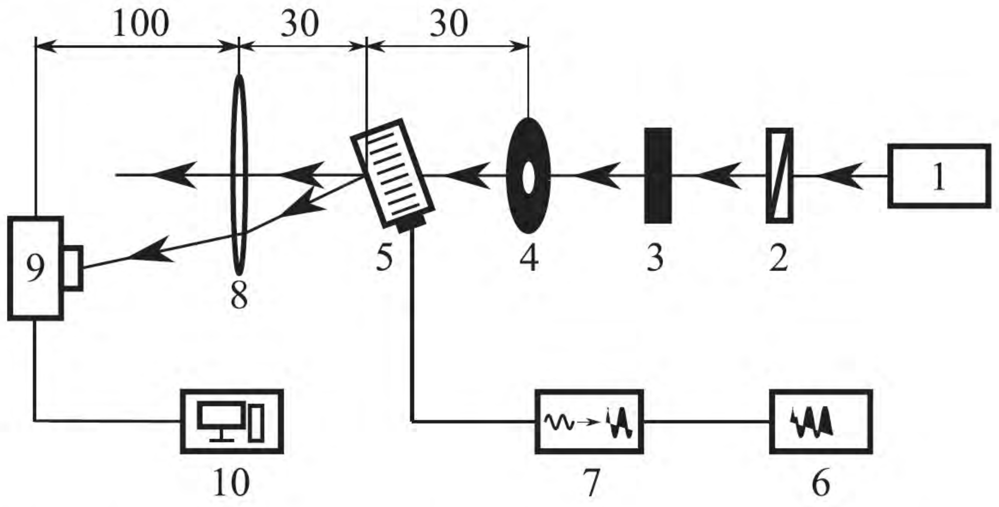


Fig. 2. Schematic drawing of the experimental setup: 1—FEL; 2—polarizer; 3—attenuator; 4—diaphragm; 5—AO cell; 6—radio-frequency generator; 7—radio-frequency amplifier; 8—lens; 9—microbolometer array; 10—computer.

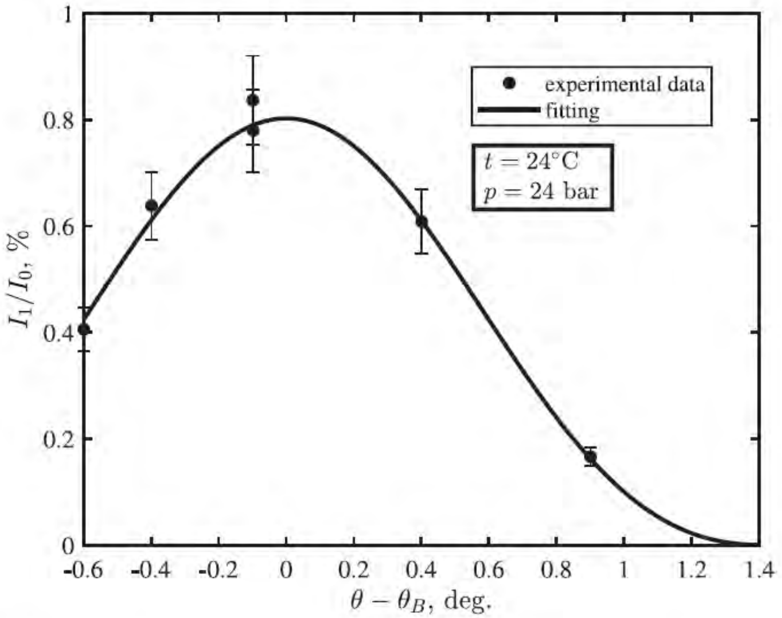
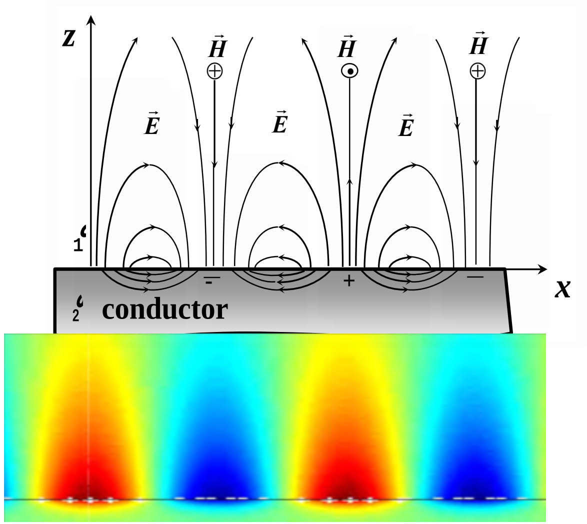


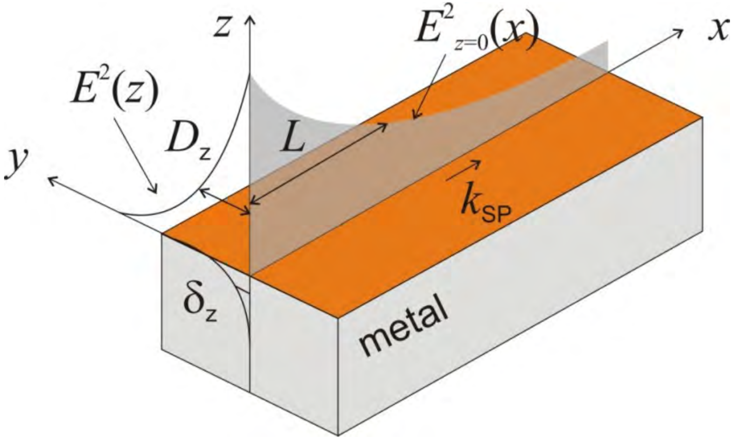
Fig. 5. Diffraction efficiency as a function of the deviation of the angle of incidence from the Bragg angle.

Nikitin, Pavel A., et al. IEEE Transactions on Terahertz Science and Technology 10.1 (2019): 44-50.

Study of surface plasmon polaritons (SPP) at NovoFEL

Study of the fundamental characteristics of surface plasmon polaritons propagating along conductor at NovoFEL has a long history. Recently, several works have been performed with the aim of finding approaches to the creation of quasi-optical plasmon devices. Two models of such devices were recently demonstrated at the FEL. In them, plasmons will have to propagate along convex surfaces. For this reason, experiments were first performed on energy loss by plasmons propagating over a cylinder.





$$\mathbf{E}_0 = \{E_{0x}, 0, E_{0z}\},$$
$$\mathbf{B}_0 = \{0, B_{0y}, 0\}.$$

$$\mathbf{E} = \mathbf{E}_0 \exp\left(\mp\kappa_{1,2} z\right)\exp\left(ik_{SP}x - i\omega t\right),$$

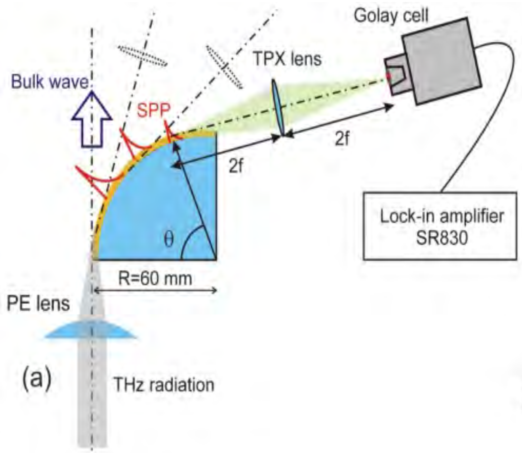
$L = 1/2\,\mathrm{Im}(k_{SP})$ – propagation length

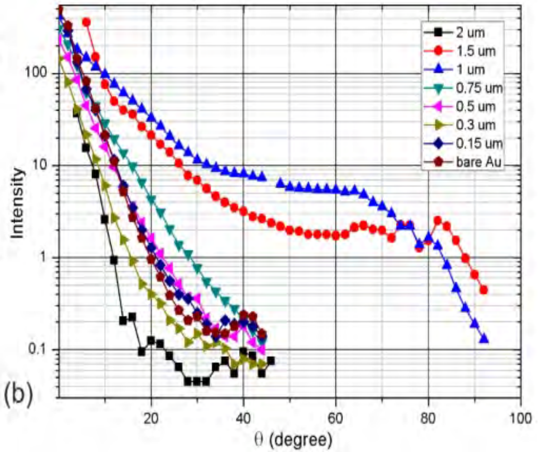
$D_z = 1/\mathrm{Re}(\kappa)$ – decay length

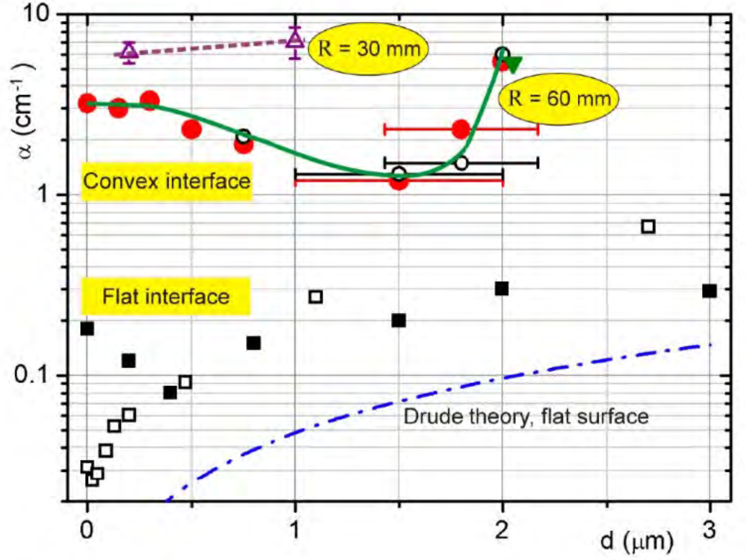
δ_z – skin depth

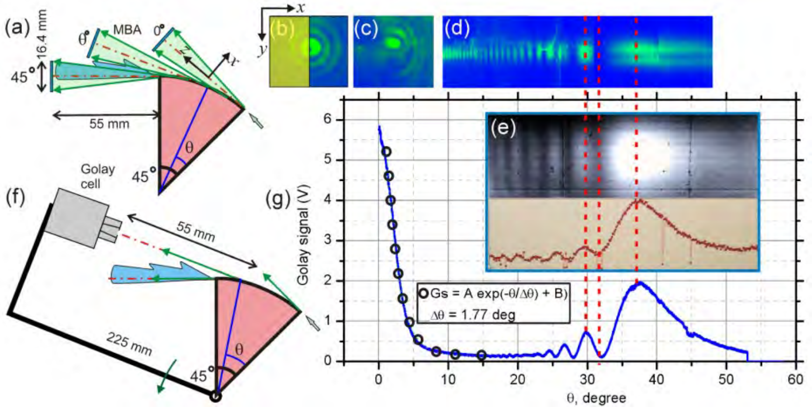
Propagation of SPPs around convex conductor

When propagating over a convex surface, plasmons lose energy in the form of ohmic and radiation losses. The latter are emitted tangentially to the surface and are proportional to the local energy of the plasmon. By measuring them with a terahertz camera, one can find the decay rate.









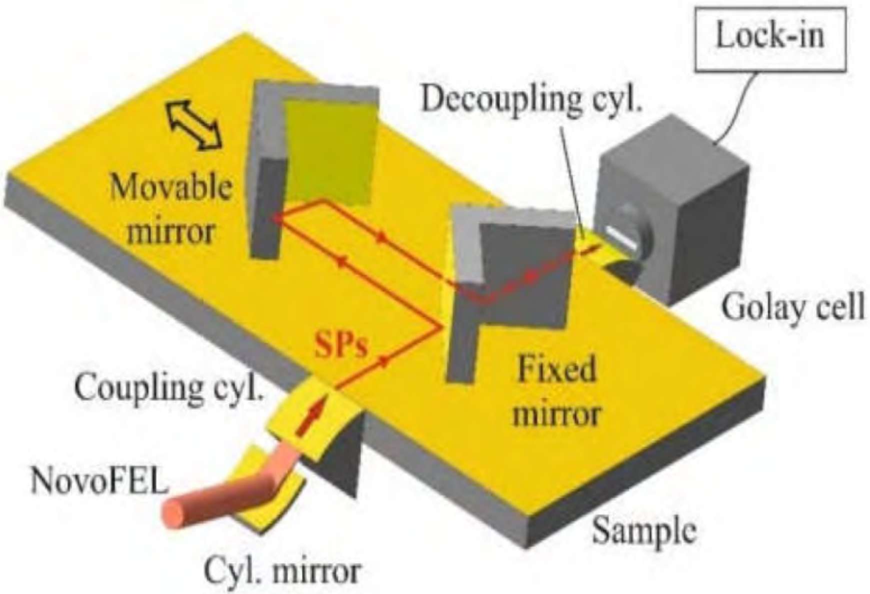
B. A. Knyazev, et al. JOSA B, Vol. 36, 1684 (2019)

Quasi-optical plasmonic devices

Properties of plasmons discovered in fundamental experiments:

- Free wave is effectively transforms into plasmon using diffraction methods
- The propagation length on the plane is tens of cm
- Plasmon can overcome gaps several centimeters long
- Plasmon is split by thin films
- Plasmon moves along curved surfaces
- Plasmon is reflected from metals and dielectrics
- Plasmon energy loss is highly dependent on the state of the surface and the presence of dielectric layers on the metal

This data allows the design of quasi-optical and sensor devices.

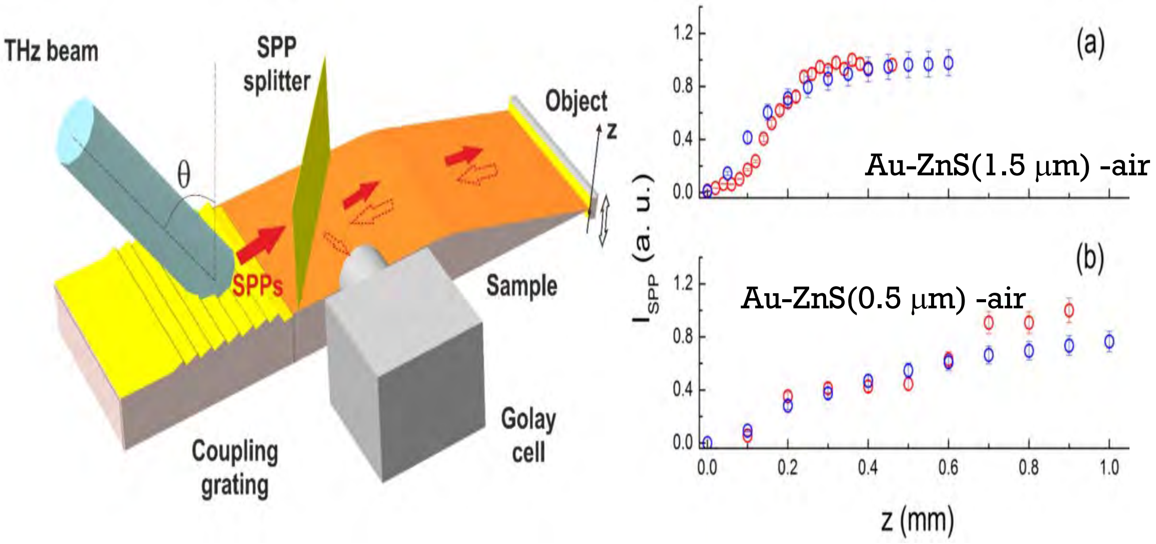


An example of a module of a quasi-optical plasmonic device for surface diagnostics.

V. V. Gerasimov, et al., JOSA B. **37** 1461-7 (2020). V. V. Gerasimov, et al., *IOP Conf. Series: Journal of Physics: Conf. Series*. **1092** 012040 (2018).

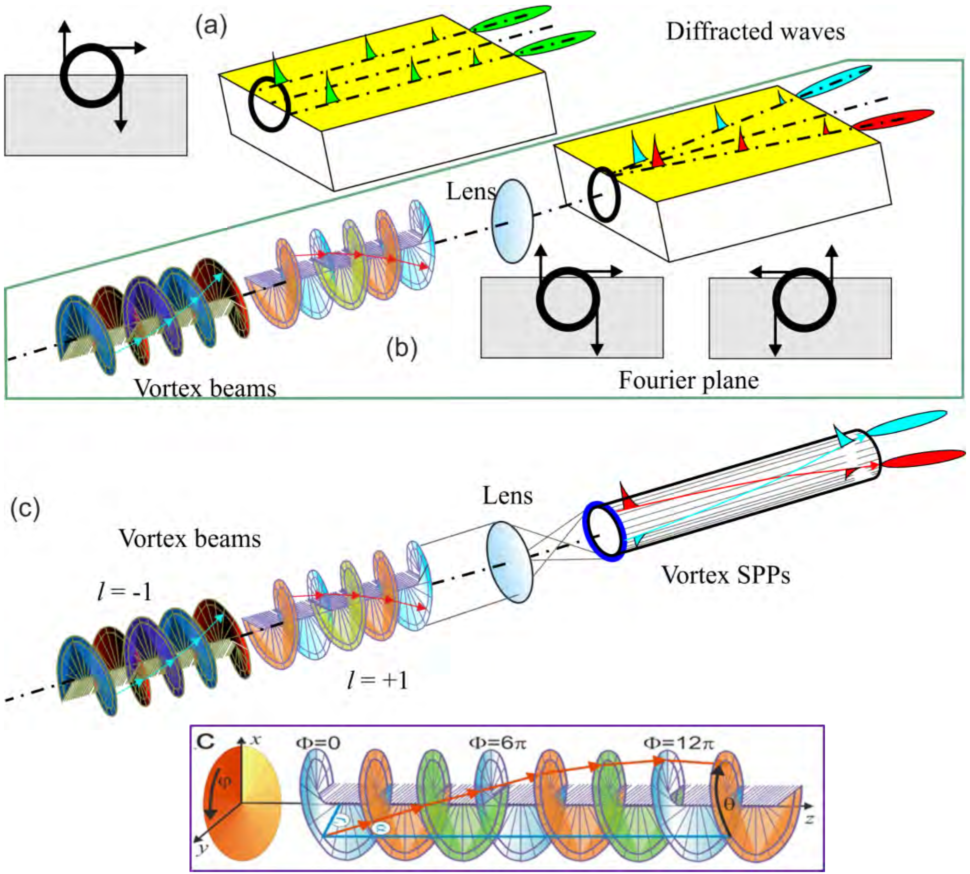
Plasmonic terahertz radar

The red circles represent the signal measured by a Golay cell, and blue - independently measured height distribution of plasmon intensity for a given thickness of the zinc sulfide layer. As can be seen, the red and blue dots coincide well, which indicates that we are indeed registering the reflected plasmon. The total length of the plasmon track was approximately 15 cm.



A. K. Nikitin, et. al., Journal of Infrared, Millimeter, and Terahertz Waves. **41**, 194-201 (2020).

Vortex beams and SPP

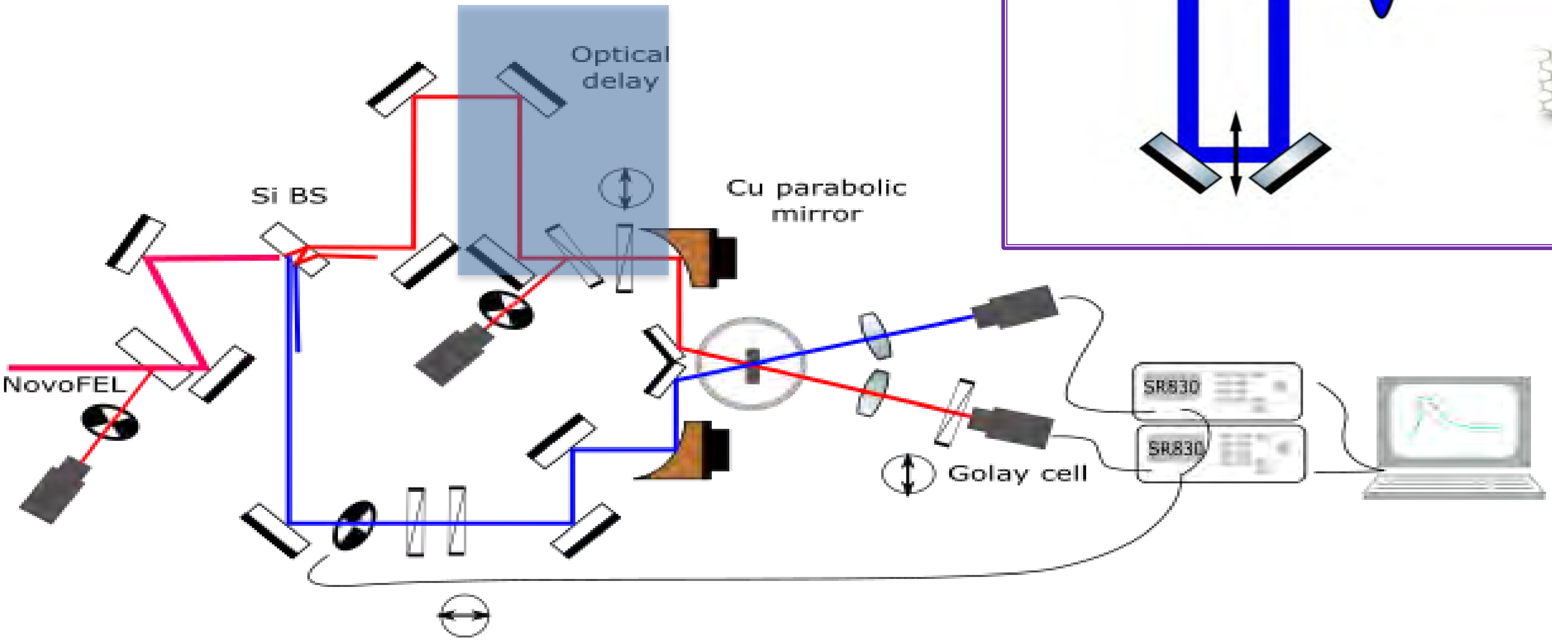


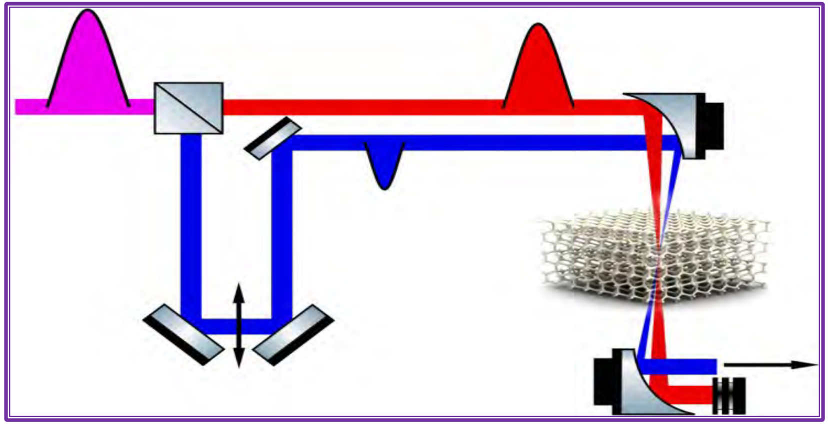
"End-fire coupling technique" (diffraction at a surface edge on Fig. a) is one of the most effective methods generating SPP. This technique can be applied to the solution of two different tasks connected with vortex beams:

- *To detect mode contents of a set of vortex beams,* they are focused onto the surface edge by a lens as "perfect beams" with equal radii. Having shifted the optical axis of the beams so that only the upper part of the beam is diffracted at the edge, we find the azimuthal components of the Poynting vector of the initial beams from the angles of deviation of the trajectories of the resulting plasmons.
- *To generate vortex plasmons at the edge of conducting cylinder*, let the perfect vortex beams diffract at the cylinder facet (Fig. c). The plasmons produced are to conserve their twist and to carry their orbital angular momenta to the waveguide end. In this manner, a multiplex plasmonic communication line can be created.

B. A. Knyazev, et al., Computer Optics 43, 992-1000 (2019).

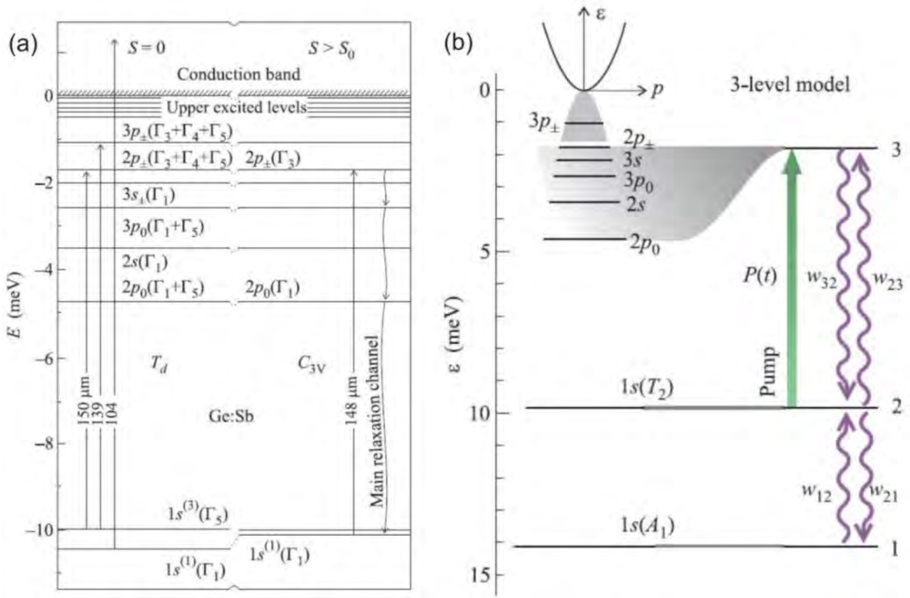
Pump-probe experiments





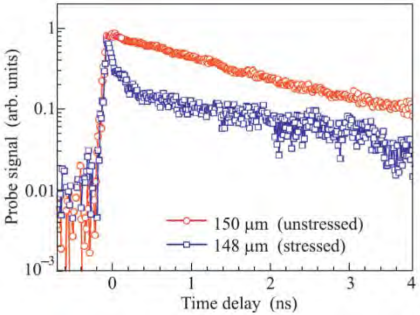
Coulomb states in semiconductors

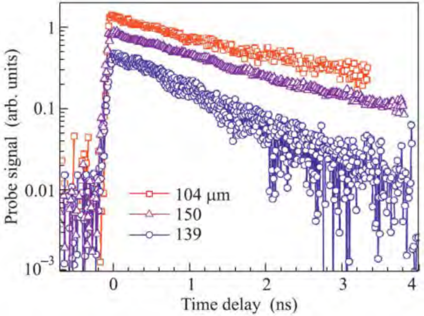
see also paper by R. Zhukavin et al. Relaxation times of donor bound electrons in silicon and germanium, Tuesday, 17:40.

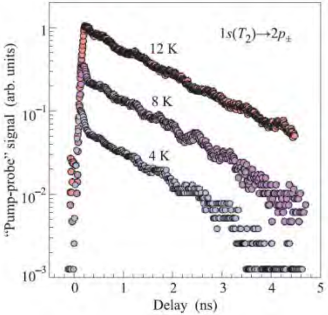


The relaxation times of the excited states of antimony donors in germanium at cryogenic temperatures by the pump-probe method were studied experimentally in the case of an undeformed crystal and under uniaxial compression at a pressure of more than 300 bar.

The relaxation times of excited states of arsenic (Fig. 18) due to their interaction with acoustic phonons in germanium at cryogenic temperatures were studied.







The results evidence that it is possible to obtain an inverse population at the transitions with wavelengths of 150 and 240 μm.

Thank you for attention

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