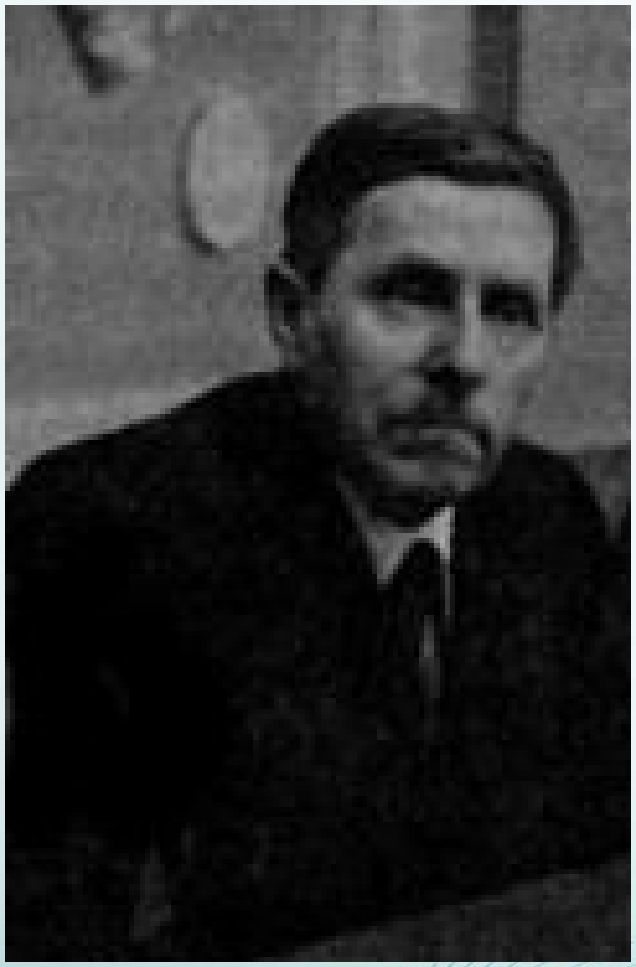
The First Fifty Years of the Laser Age of Nonlinear Optics in M.V. Lomonosov Moscow State University

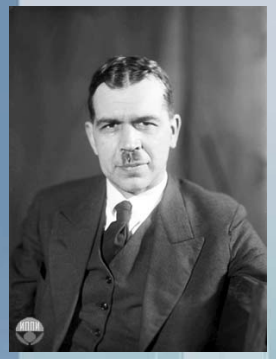
V.A. Makarov

Physics Faculty and International Laser Center, M.V. Lomonosov Moscow State University,



S.I. Vavilov, V.L. Levshin. Zeitschrift fur Physik, 35, 932 (1926).

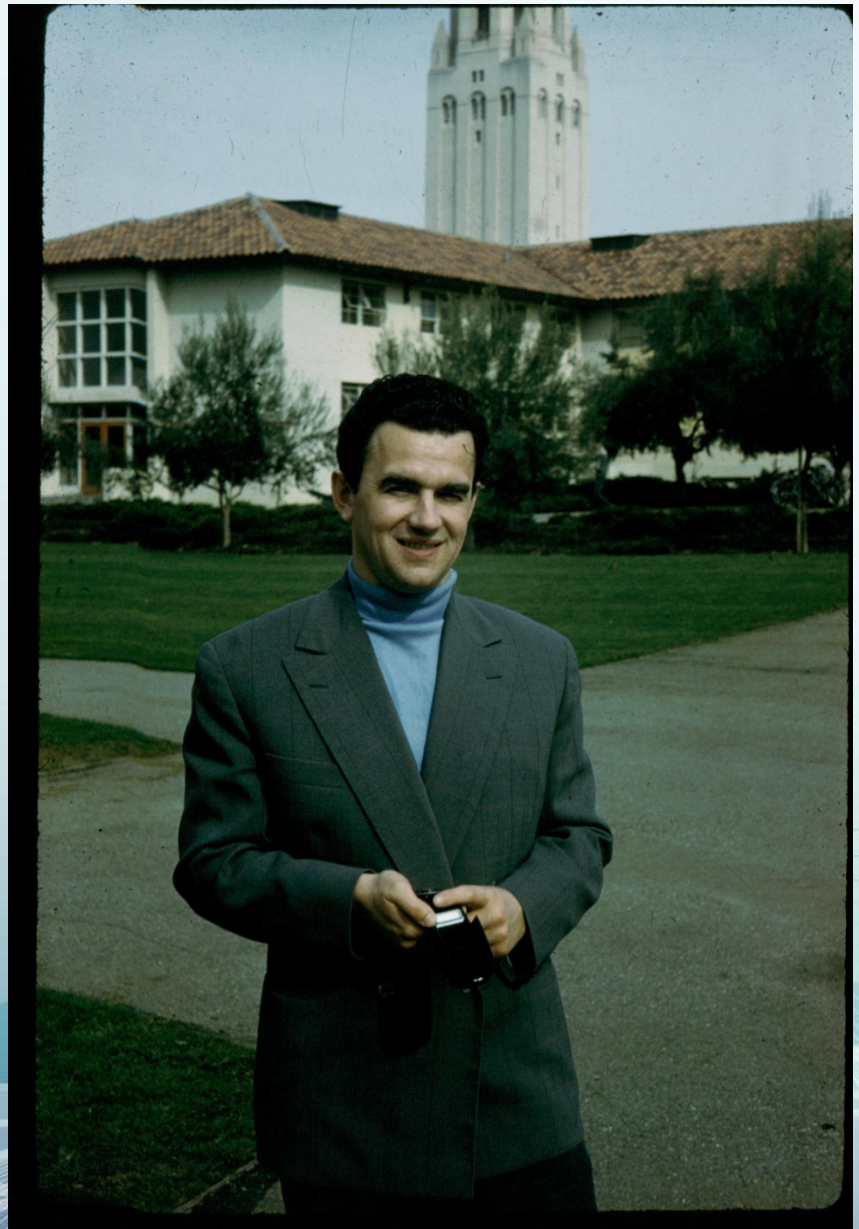
The nonlinearity in an absorbing medium should be observable not only with respect to absorption. The latter is related to dispersion, and therefore the velocity of light propagation in the medium should, generally speaking, also depend on the power of light. For the same reason, the dependence on the light power, i.e., superposition violation, should also be observable in the general case in other optical properties of the medium in birefringence, dichroism, rotatory power, etc.”



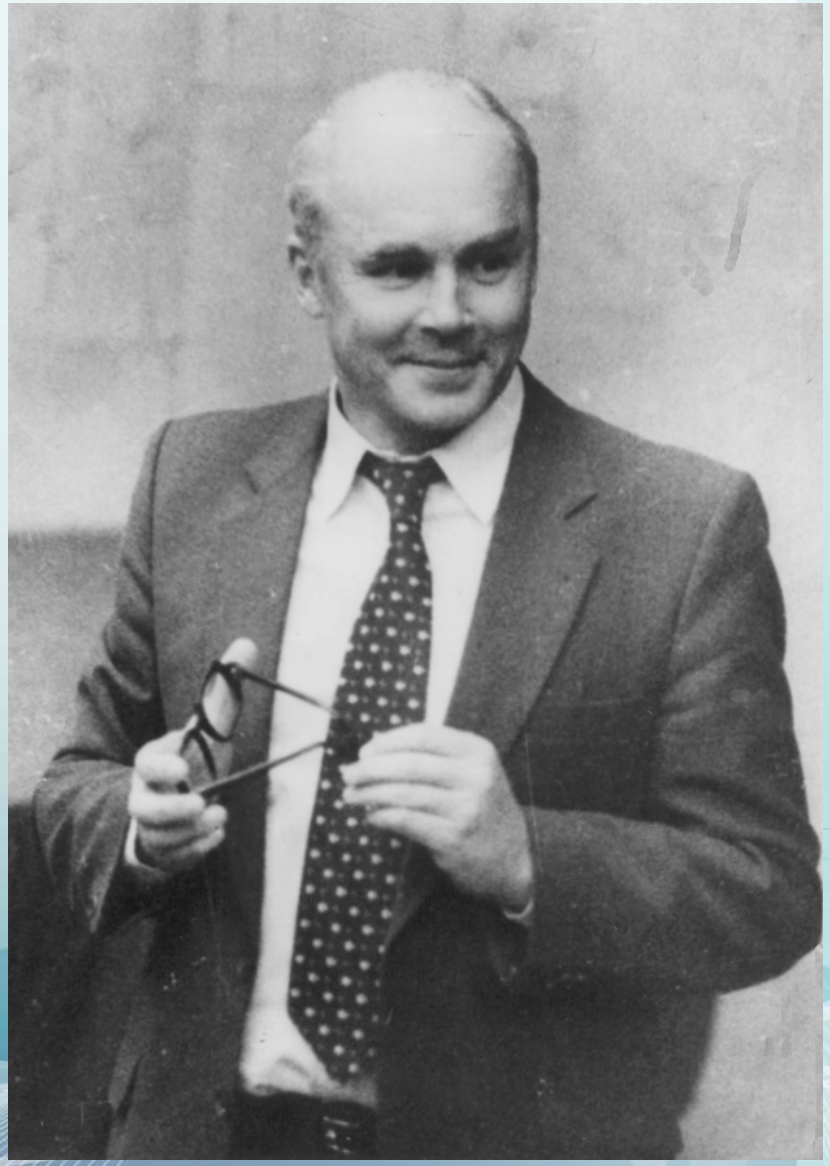
S.I. Vavilov

“Microstructure of Light; Investigations and Studies”, USSR Academy of science, 1950 (marked with a first-degree Stalin Prize).

In the beginning of 1962 the team of young scientists interested in “laser” science development in MSU have emerged at the Faculty of Physics. R.V.Khokhlov become the ideologist of this team. At that time he was the associate professor of oscillations chair and he completed his thesis for the degree of doctor of science.



One of his coworkers in laser science was S.A.Akhmanov, assistant of the radiophysics chair. Later, this team leaded by Khokhlov was called the nonlinear optics laboratory of the Faculty of Physics of MSU. It was the first laboratory of such kind in Soviet Union.



Physics Faculty of MSU in 1960

Material equation in nonlinear medium

$$\vec{P} = \hat{\chi}^{(1)}\vec{E} + \hat{\chi}^{(2)}\vec{E}\vec{E} + \hat{\chi}^{(3)}\vec{E}\vec{E}\vec{E} + \ldots$$

(1960)

$$\vec{P} = \hat{\chi}^{(1)}\vec{E} + \hat{\chi}^{(2)}\vec{E}\vec{E} + \hat{\chi}^{(3)}\vec{E}\vec{E}\vec{E} + \ldots +$$
$$+ \hat{\gamma}^{(1)}\vec{\nabla}\vec{E} + \hat{\gamma}^{(2)}\vec{E}\vec{\nabla}\vec{E} + \hat{\gamma}^{(3)}\vec{E}\vec{E}\vec{\nabla}\vec{E} + \ldots$$

S.A. Akhmanov, V.I. Zharikov (1967)

Material equation in nonlinear medium

$$P_i(\vec{\mathbf{r}},t) = \int_{-\infty}^{t} dt' \int_V d\vec{\mathbf{r}}' \chi_{ij}^{(1)}(t,t',\vec{\mathbf{r}},\vec{\mathbf{r}}') E_j(t',\vec{\mathbf{r}}') +$$

$$+ \int_{-\infty}^{t} dt' \int_{-\infty}^{t'} dt'' \iint_V d\vec{\mathbf{r}}' d\vec{\mathbf{r}}'' \chi_{ijm}^{(2)}(t,t',t'',\vec{\mathbf{r}},\vec{\mathbf{r}}',\vec{\mathbf{r}}'') E_j(t',\vec{\mathbf{r}}') E_m(t'',\vec{\mathbf{r}}'') +$$

$$+ \int_{-\infty}^{t} dt' \int_{-\infty}^{t'} dt'' \int_{-\infty}^{t''} dt''' \iiint_V d\vec{\mathbf{r}}' d\vec{\mathbf{r}}'' d\vec{\mathbf{r}}''' \chi_{ijml}^{(3)}(t,t',t'',t''',\vec{\mathbf{r}},\vec{\mathbf{r}}',\vec{\mathbf{r}}'',\vec{\mathbf{r}}''') \times$$

$$\times E_j(t',\vec{\mathbf{r}}') E_m(t'',\vec{\mathbf{r}}'') E_l(t''',\vec{\mathbf{r}}''') + \ldots$$

(2010)

Second harmonic generation

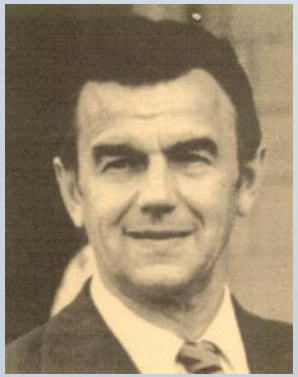
P. Franken et al., 1961, Phys. Rev. Letts.

N. Bloembergen et al., 1962, Phys. Rev.

R.V. Khokhlov, 1962, Radiotekh. Elektron.

R. Terhune et al., 1963,

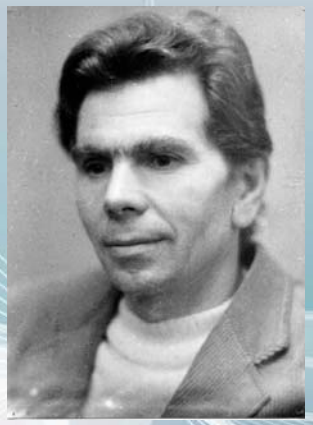
Phys. Rev. Letts.

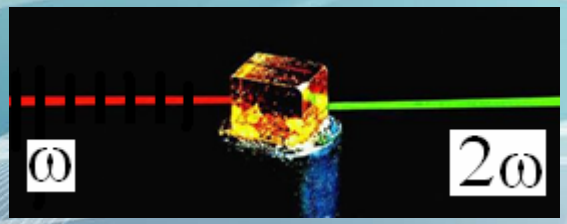


S.A. Akhmanov, A.I. Kovrigin

A. Piskarskas, R.V. Khokhlov,

1963, JETP Letts.



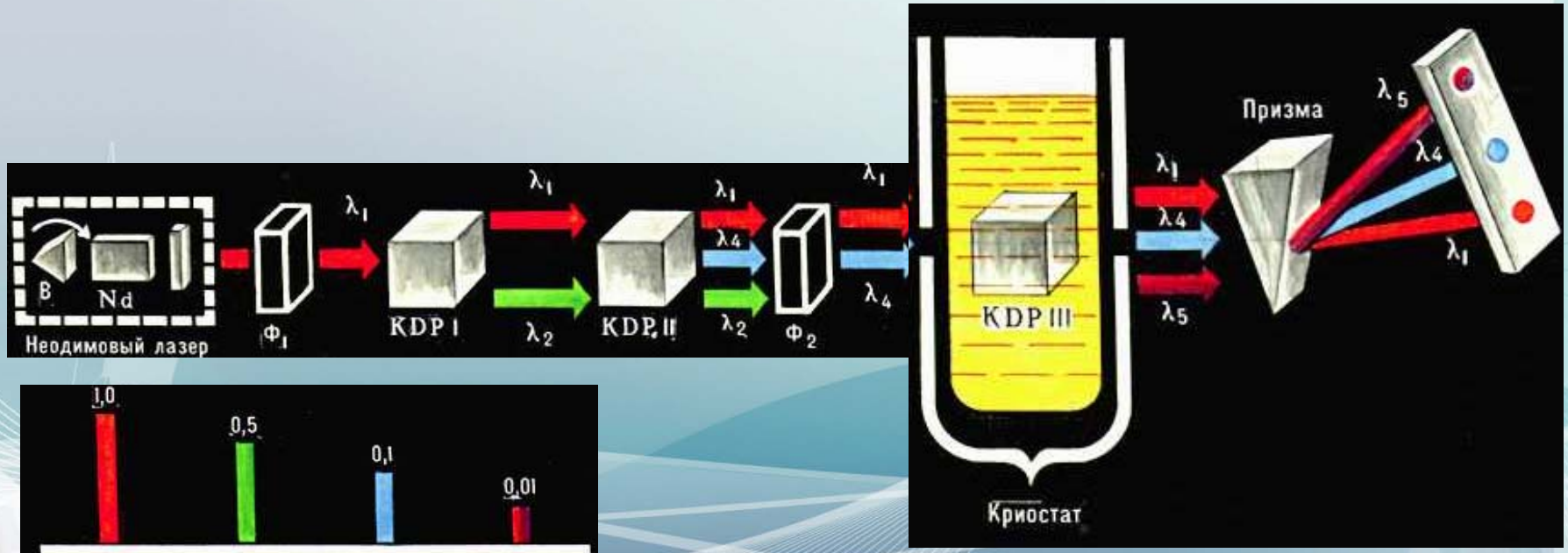


The third and high harmonics generation

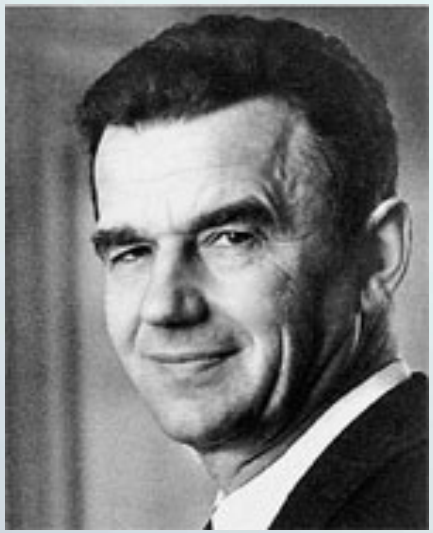
GENERATION OF COHERENT RADIATION AT λ = 2120 Å BY CASCADE FREQUENCY CONVERSION

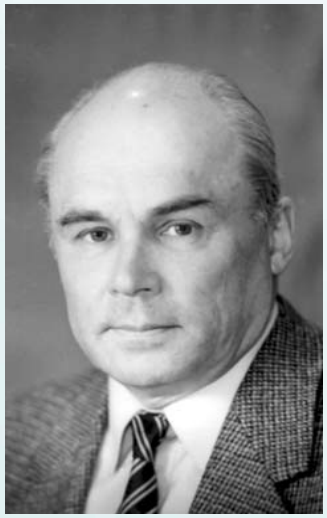
A. G. Akmanov, S. A. Akhmanov, B. V. Zhdanov, A. I. Kovrigin, N. K. Podsotskaya, and R. V. Khokhlov
Moscow State University
Submitted 23 July 1969
ZhETF Pis. Red. 10, No. 6, 244 - 249 (20 September 1969)

1. The purpose of the present paper is to report the results of an experimental investigation that has led to the development of a source of intense coherent radiation at a wavelength λ = 2120 Å. Ultraviolet (UV) radiation of ∿ 1 kW power was obtained by synchronous cascade generation of the fifth harmonic of the radiation of a neodymium laser in a KDP



Optical parametric oscillators





1962

PHYSICAL REVIEW
LETTERS

VOLUME 14 — 14 JUNE 1965 — NUMBER 24

TUNABLE COHERENT PARAMETRIC OSCILLATION IN $LiNbO_3$ AT OPTICAL FREQUENCIES

J. A. Giordmaine and Robert C. Miller
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received 11 May 1965)

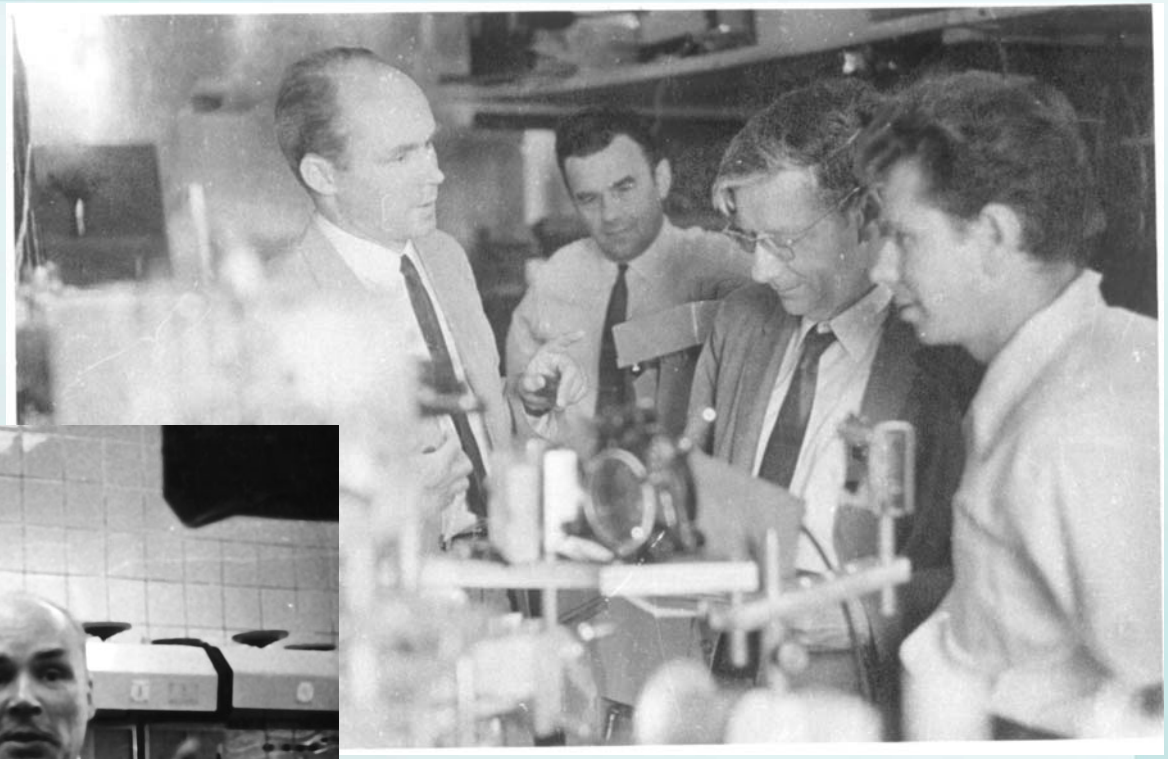
1965, Phys. Rev. Letts.

OBSERVATION OF PARAMETRIC AMPLIFICATION IN THE OPTICAL RANGE

S. A. Akhmanov, A. I. Kovrigin, A. S. Piskarskas, V. V. Fadeev, and R. V. Khokhlov
Physics Faculty, Moscow State University
Submitted 23 July 1965

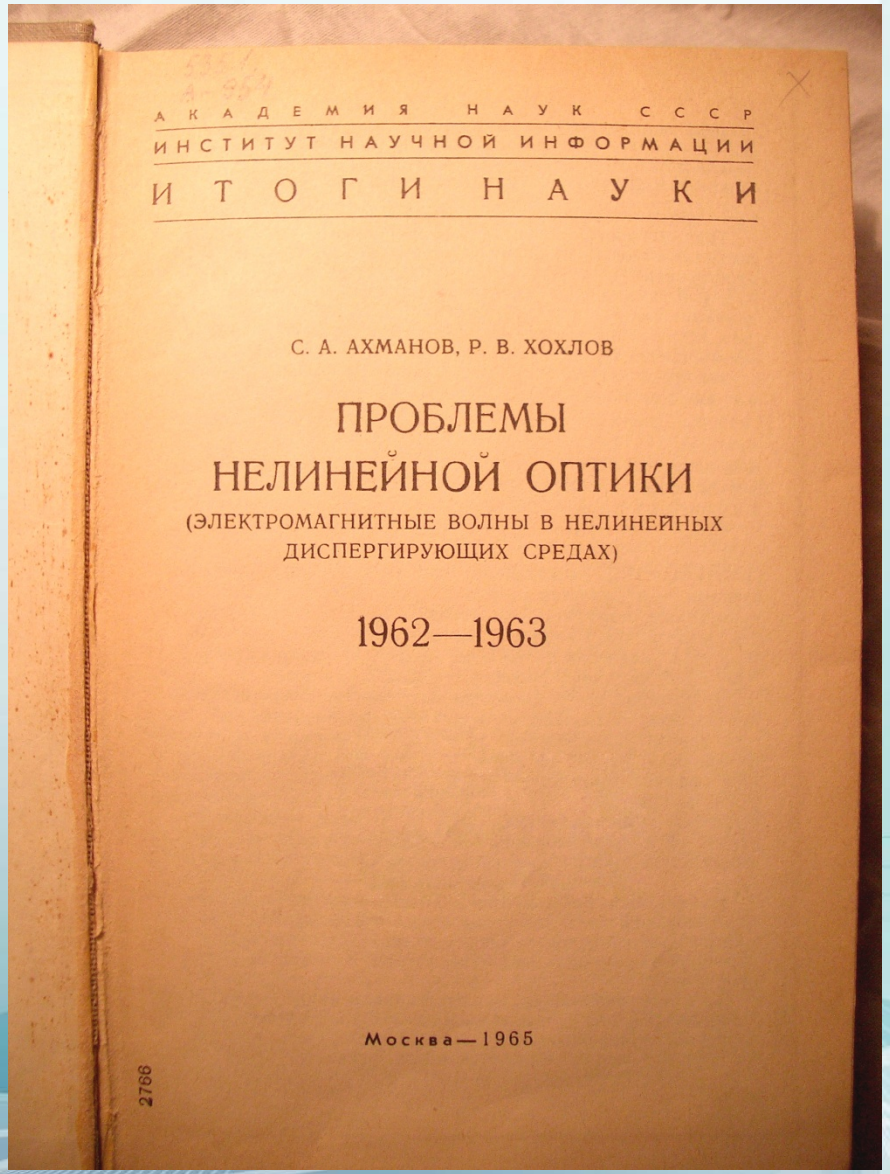
We report here the results of an experiment in which we observed directly parametric amplification of an optical signal with wavelength $\lambda_s = 1.06\ \mu$ in a KDP crystal excited by an intense pump wave with $\lambda_p = 0.53\ \mu$. The feasibility of such an effect in the optical band and its theory were detailed in [1-3]; results of experiments in which parametric amplification at wavelength $\lambda_s = 0.63\ \mu$ has been indirectly registered are described in [4].

1965, JETP Letts.

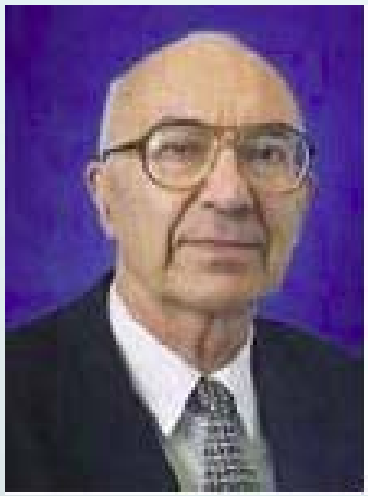


Prominent results obtained in the field of nonlinear interaction of electromagnetic waves and number of principal experiments provided the world-wide reputation of the laboratory of nonlinear optics.

At that time S.A. Akhmanov and R.V. Khokhlov have written the first in the world monograph on nonlinear optics: “The problems of nonlinear optics” (1964). This book reviewing the achievements of nonlinear optics during the first “laser” years greatly promoted rapid development of this new field of science in USSR.



Laser beam self-focusing



OBSERVATION OF SELF-FOCUSING OF LIGHT IN LIQUIDS

1965, JETP Letts.

N. F. Pilipetskii and A. R. Rustamov
Moscow State University
Submitted 3] May 1965

In 1962 G. A. Askar'yan considered one of the important problems involved in the effect of a beam of intense radiation on a medium. He has shown that intense radiation can lead to a differential between the properties of the medium inside and outside the beam. The latter creates conditions suitable for waveguide propagation of the beam, thereby eliminating the geometrical and diffractional divergences. This interesting phenomenon was called by him self-focusing of an electromagnetic beam.

OBSERVATION OF SELF-FOCUSING OF LIGHT IN LIQUIDS

N. F. Pilipetskii and A. R. Rustamov
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Submitted 3] May 1965

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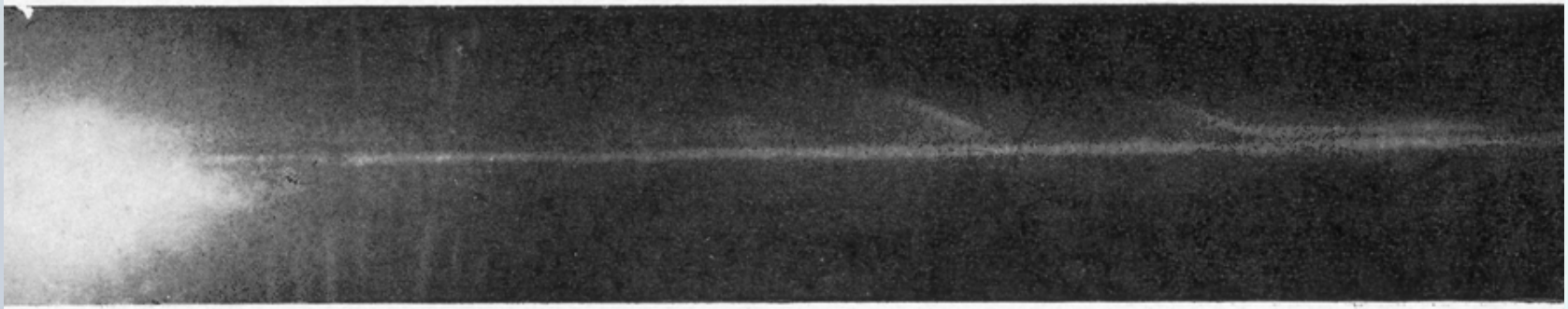
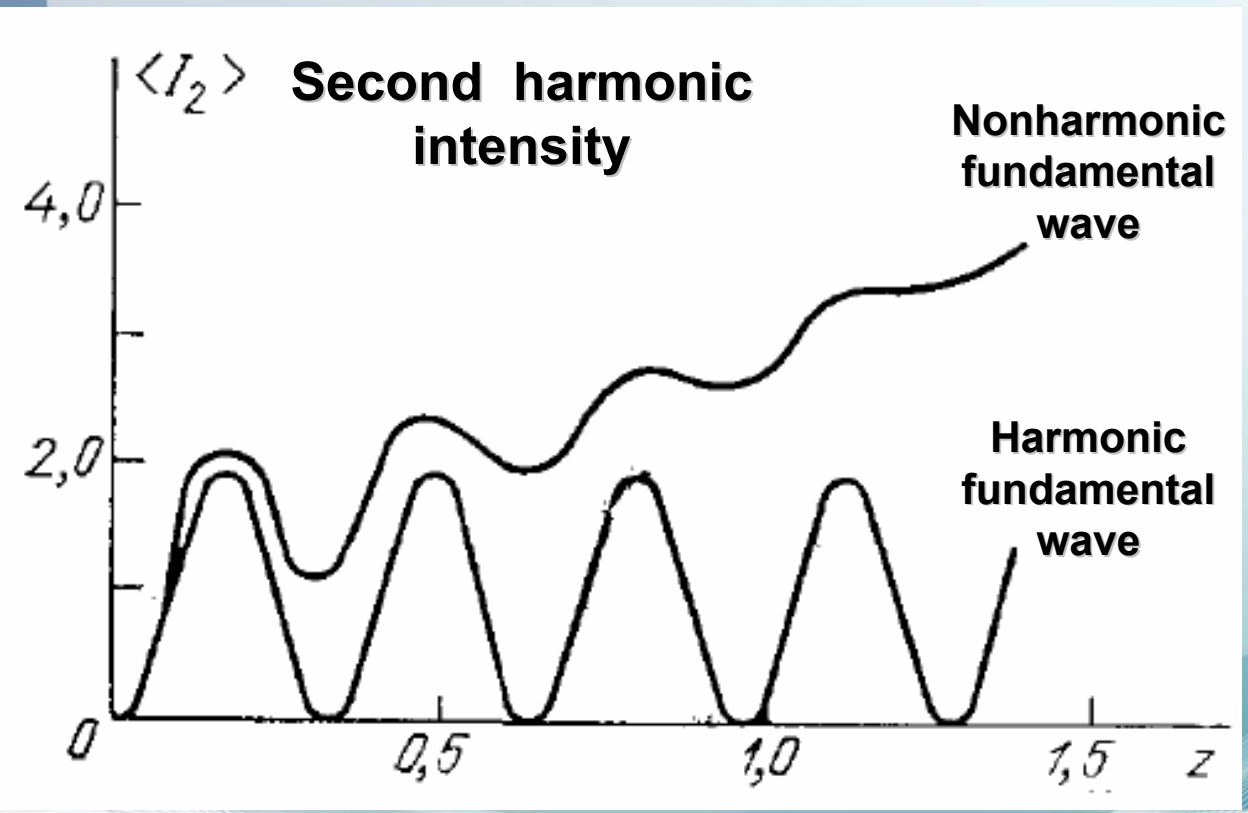


Nonlinear laser spectroscopy

S.A. Akhmanov, N.I. Koroteev
“Methods of Nonlinear Optics in Light Scattering Spectroscopy”, Nauka publisher , 1981.

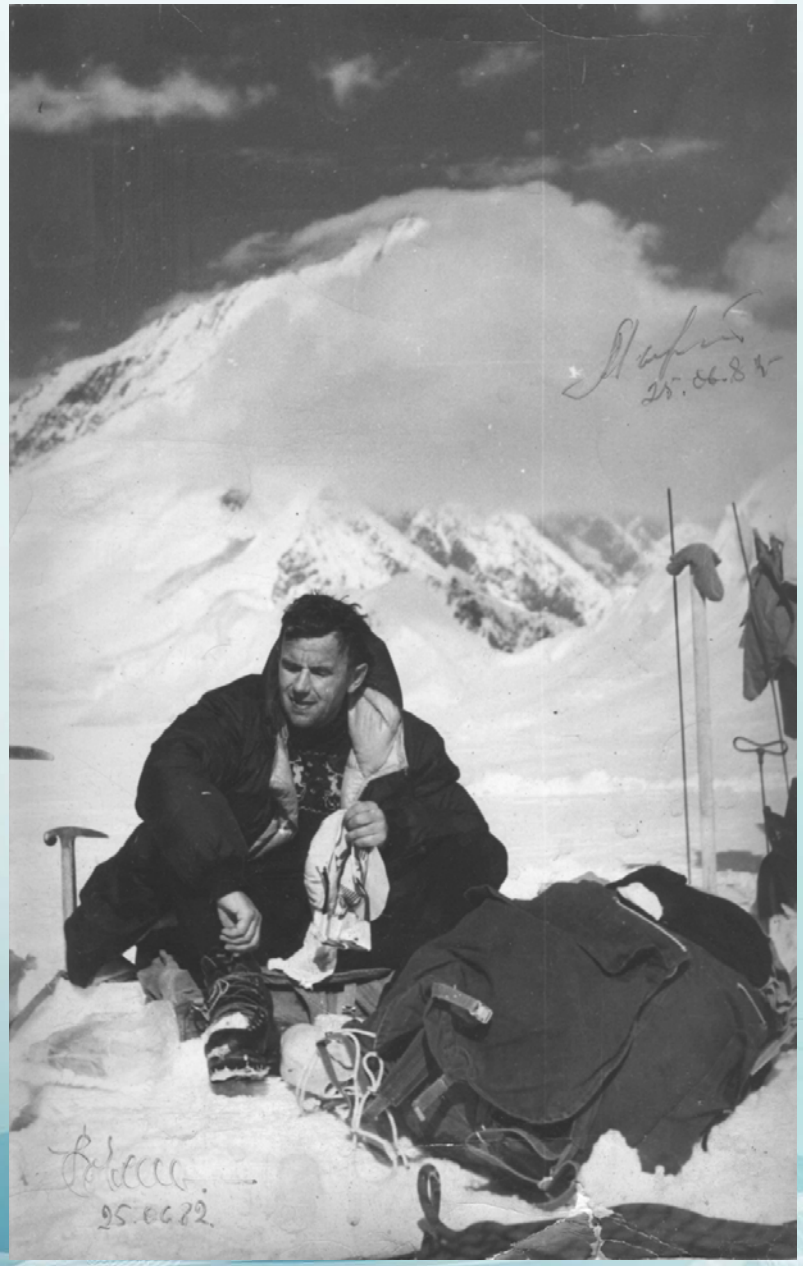
Statistical nonlinear optics

A.S. Akhmanov, A.S. Chirkin, 1966, Radiotekh. Elektron



After R.V. Khokhlov's tragical death in 1977 professor S.A. Akhmanov has headed the incorporated general physics and wave processes chair and managed it before his death in 1991. The group of scientists has formed a new chair – the quantum electronics chair headed by the academician L.V. Keldysh

Now both chairs are located in the Nonlinear Optics Building, which construction have been initiated by Khokhlov and finished in 1980.



1947–1998

In 1992 – 1998 General physics and wave processes chair and International laser center of Lomonosov Moscow State University (which was founded in 1989 owing to the efforts of S.A. Akhmanov) headed by N.I. Koroteev.

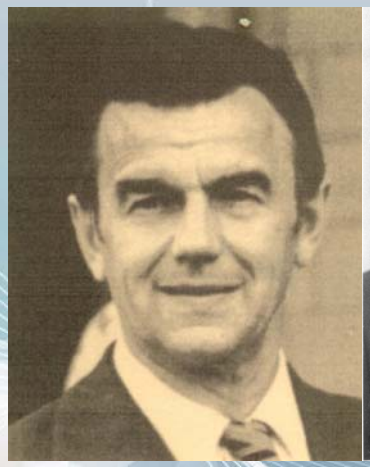
Owing to his talent the Chair and the International laser center have withstood during the hard period of 90th years, when Russian science and education were experiencing many difficulties.

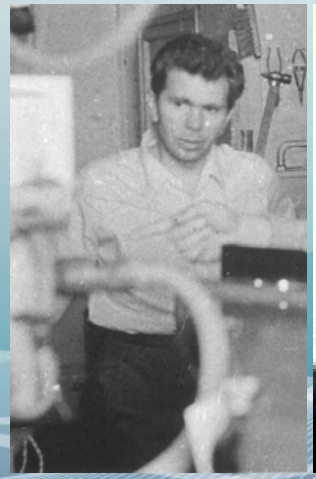
Achievements, determining the current status of modern nonlinear optics

The mathematical basics of almost all the linear and nonlinear wave optics nowadays is the slowly varying envelope method, proposed by R.V. Khokhlov in 1959-1961. This method was developed in research works of R.V. Khokhlov, S.A. Akhmanov, A.P. Sukhorukov and their disciples.

Achievements, determining the current status of modern nonlinear optics

The idea of parametric amplification and generation of light proposed by R.V. Khokhlov and S.A. Akhmanov in 1962 become the foundation of numerous theoretical and experimental developments. The first light parametric oscillator in Russia started in 1965.





Achievements, leading to the new trends in nonlinear optics and laser physics

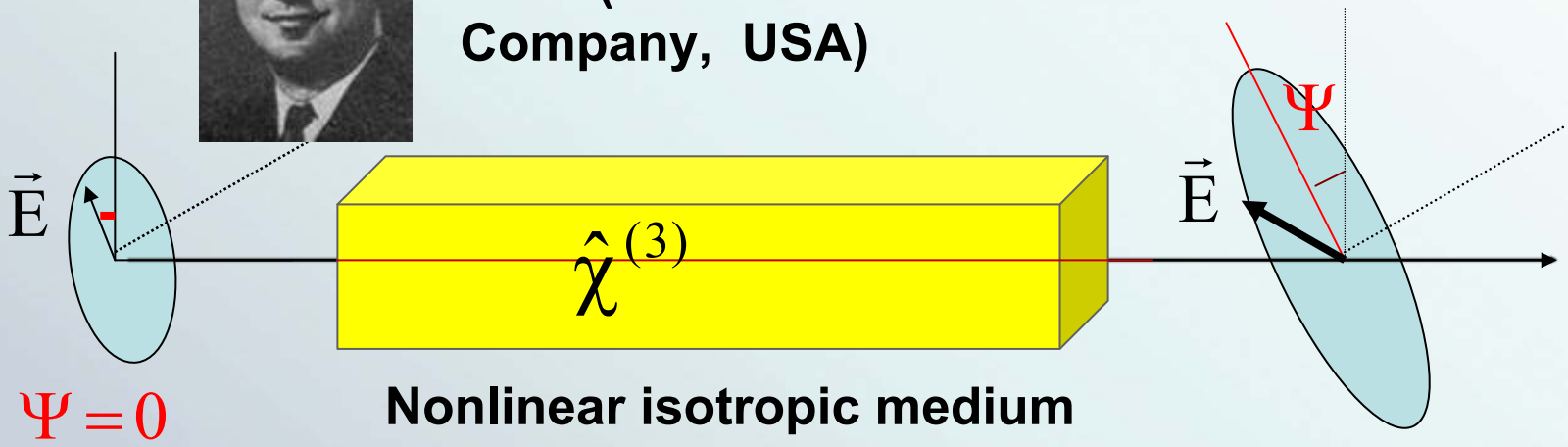
- Application of nonlinear optics in the development of the wave-mixing spectroscopy methods for the medium diagnostics (including principally new method, coherent antistokes light scattering (CARS)).
- Statistical nonlinear optics.
- Development of the numerical solution methods for the problems of statistical nonlinear optics.



Nonlinear polarization optics

R.W. Terhune, 1964 (Ford Motor Company, USA)

Nonlinear rotation of polarization ellipse

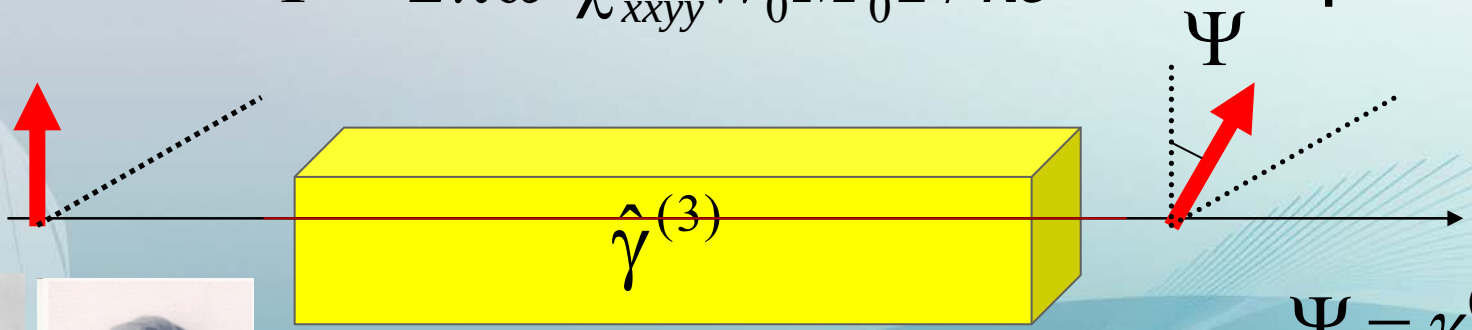


$\Psi = 0$

Nonlinear isotropic medium

$$\Psi = 2\pi\omega^2\chi^{(3)}_{xxyy}W_0M_0z/kc^2$$

Nonlinear optical activity



$$\Psi = \gamma^{(3)}W_0z$$

Nonlinear medium with spatial dispersion

Achievements, leading to the new trends in nonlinear optics and laser physics

The material equation in the approximation of the first order on the spatial dispersion parameter

$$P_i^{\mathrm{NL}} = \chi_{ijl}^{(2)} E_j E_l + \chi_{ijlm}^{(3)} E_j E_l E_m + \chi_{ijlmn}^{(4)} E_j E_l E_m E_n + \ldots +$$

SHG & SFG

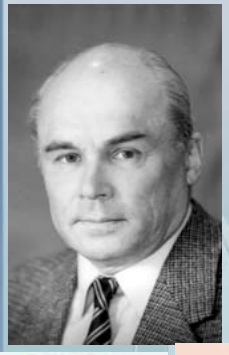
THG, CARS, self-focusing, nonlinear optical rotation and deformation

BioCARS etc.

$$+ \gamma_{ijlm}^{(2)} \nabla_j E_l E_m + \gamma_{ijlmn}^{(3)} \nabla_j E_l E_m E_n + \gamma_{ijlmnp}^{(4)} \nabla_j E_l E_m E_n E_p + \cdots$$

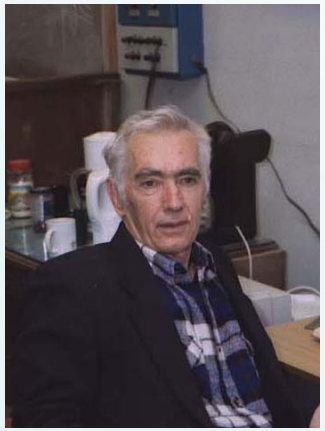
Nonlinear rotation and deformation of polarization ellipse

Symmetry classes	1	2	3	4
$4, 422, 432, 3, 6, 23, \infty$	+	+	+	+
$32, 622, \infty 2, \infty\infty$	+		+	
$\bar{4}, \bar{4}2m, \bar{4}3m, 4mm$	+	+	+	+
$4/m, \bar{3}, \bar{6}, 6/m, m3m, \infty/m, m3, 4/mmm$		+	+	
$\bar{3}m, \bar{6}m2, 6/mmm, \infty/mm, \infty\infty m$			+	
$3m, 6mm, \infty m$			+	+



Nonlinear optical processes as the basis for creation powerful laser systems



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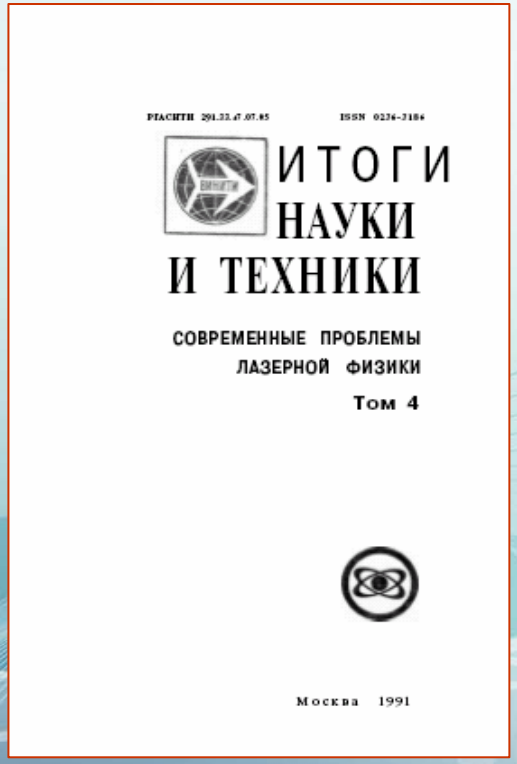


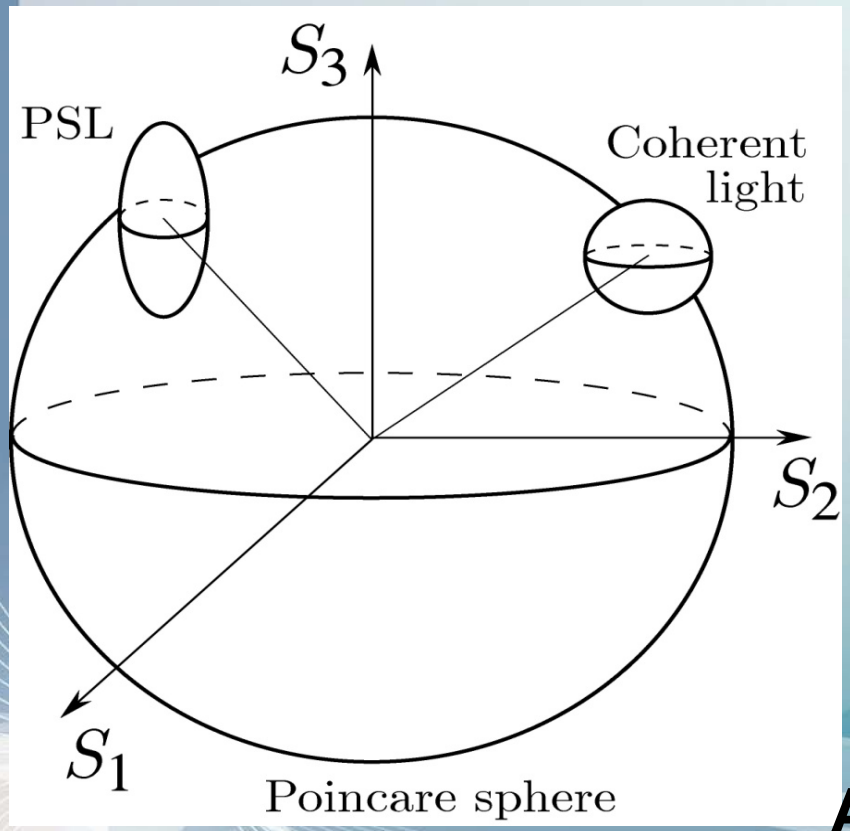
S.A. Akhmanov, V.M. Gordienko, V.T. Platonenko et al, Quant. Electron., 1986.

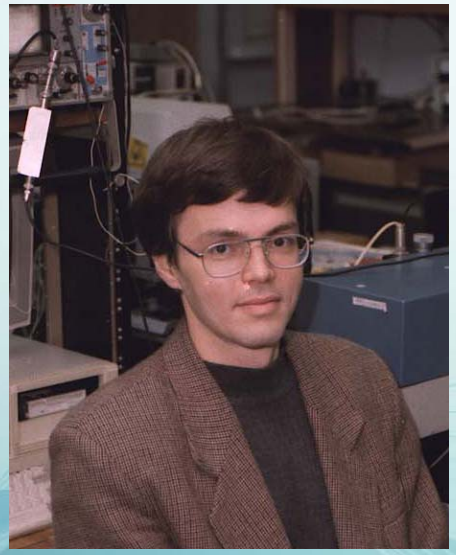
Polarization–compressed light

$$\hat{E}(t) = iC\left(\vec{e}_V \hat{a}_V + \vec{e}_H \hat{a}_H\right)e^{-i(\omega t - kz)} + \text{c.c.}$$

Stokes parameters

$$\hat{S}_0 = \hat{a}_V^+ \hat{a}_V + \hat{a}_H^+ \hat{a}_H, \quad \hat{S}_2 = \hat{a}_V^+ \hat{a}_H + \hat{a}_H^+ \hat{a}_V,$$
$$\hat{S}_1 = \hat{a}_V^+ \hat{a}_V - \hat{a}_H^+ \hat{a}_H, \quad \hat{S}_3 = i\left(\hat{a}_H^+ \hat{a}_V - \hat{a}_V^+ \hat{a}_H\right)$$

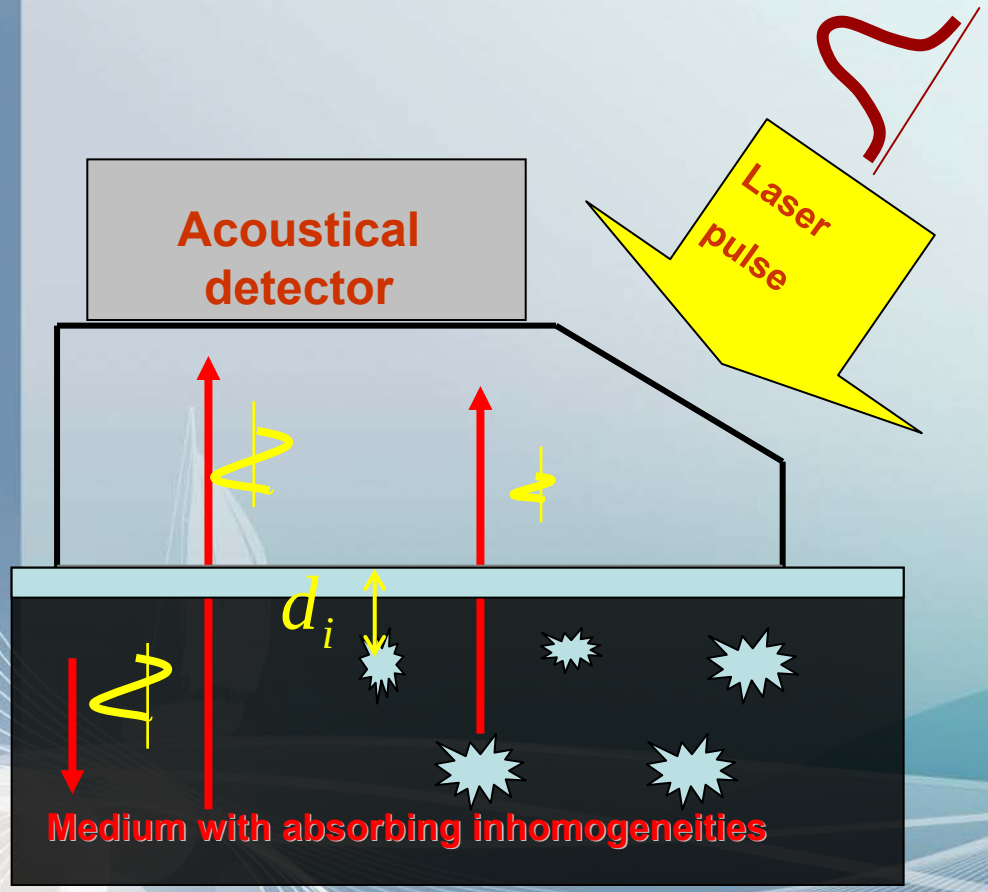


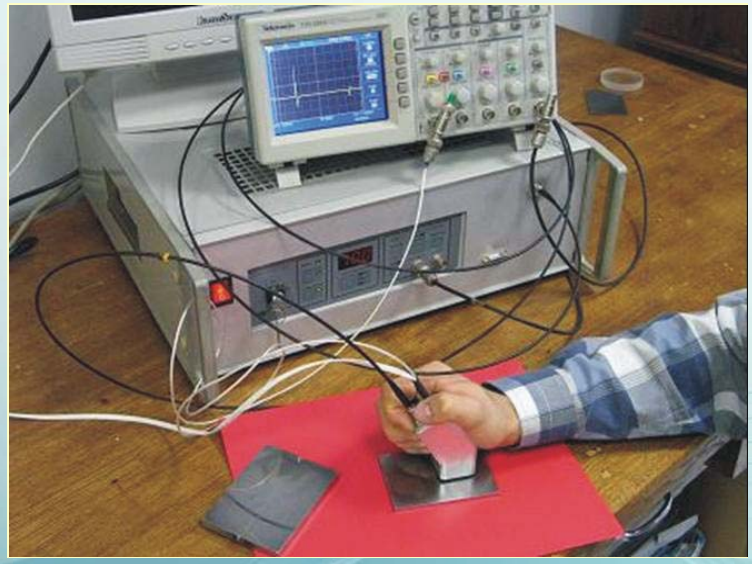


A.S. Chirkin, D.Yu. Parashuk,1993

Achievements, leading to the new trends in nonlinear optics and laser physics

Physical principles and devices for the optoacoustic diagnostics





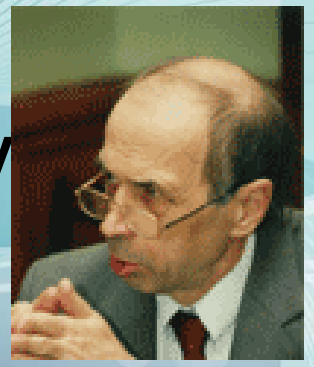
Public recognition of the prominent results of MSU scientists in nonlinear optics

The Lenin prize (highest state prize in USSR)

1970. R.V. Khokhlov and S.A. Akhmanov

“For the investigation of nonlinear coherent interactions in optics”

1978. A.P. Sukhorukov “For the discovery and investigation of self- focusing (with G.A. Askaryan, V.V. Korobkin, V.N. Lugovoy N.F. Pilipetsky, V.I. Talanov)



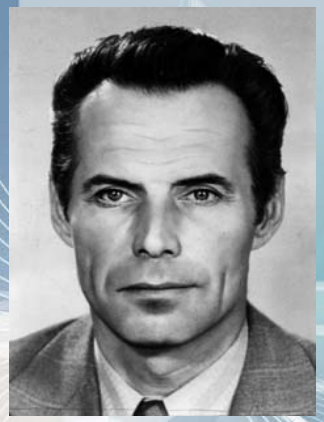
The USSR State Prize

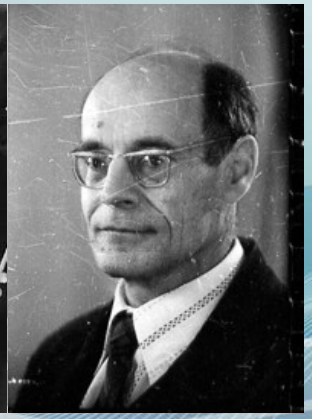
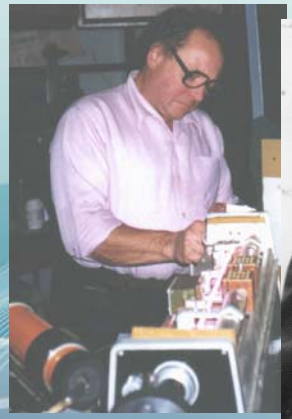
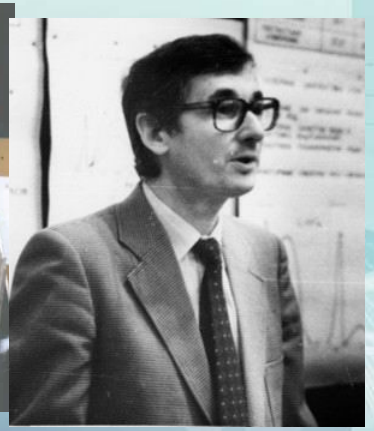
1975 

E.S. Voronin, V.S. Solomatin, Yu.A. Il'inskii "For the series of works devoted to the design of nonlinear optical converters of IR-signals and images to visible range" (with I.N.Matveev, N.D. Ustinov)

1978 

D.N. Klyshko, A.N. Penin, V.V. Fadeev "For the discovery and investigation of parametric light scattering and its application in spectroscopy and metrology"

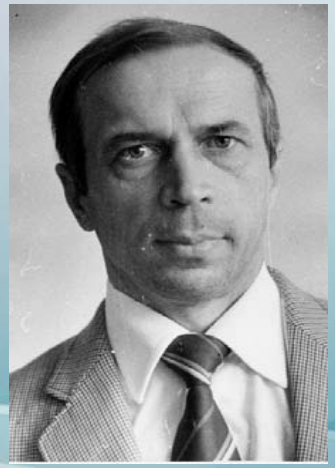


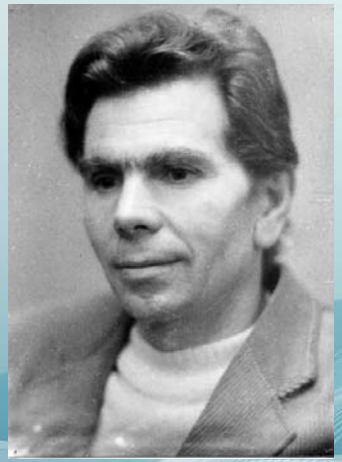





The USSR State Prize

1984

A.I. Kovrighin, A.P. Sukhorukov “For the theory and design of new generation of high-efficiency nonlinear optical converters” (with B.V. Bokut’, V.D. Volosov, V.G. Dmitriev, A.A. Kulevskii, A.S. Piskarskas, T.R. Rustamov, T. Usmanov, G.I. Freidman)





The Russian Federation State Prize

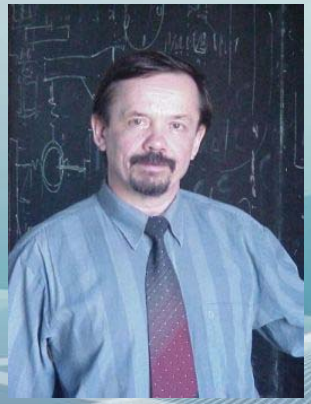
O.V.Rudenko, A.S. Chirkin “Dynamics of intense noise

waves and nonlinear patterns in media without dispersion” (with A.N. Malakhov, A.I. Saichev, S.A. Ribak, E.N. Pelinovsky,, V.E. Fridman)

O.A. Aktsipetrov, P.K. Kashkarov, V.I. Panov

2002 “Electronic and atomic processes on the surfaces of

solid bodies” (with Yu. Aristov, A.M. Ionov, V.G. Lifshic, V.N. Ovsuk)



Public recognition of the prominent results of MSU scientists in nonlinear optics

Lenin's komsomol prizes and State awards of Russian Federation for the young scientists

A.V. Andreev, A.M. Zheltikov, V.N. Zadkov, A.A. Karabutov, S.A. Shlenov, A.B. Fedotov

M.V. Lomonosov prize (MSU)

S.A. Akhmanov, V.I. Emel'yanov, V.P. Kandidov, A.A. Karabutov, N.I. Koroteev, V.A. Makarov, O.V. Rudenko, A.P. Sukhorukov, R.V.Khokhlov, A.S. Chirkin

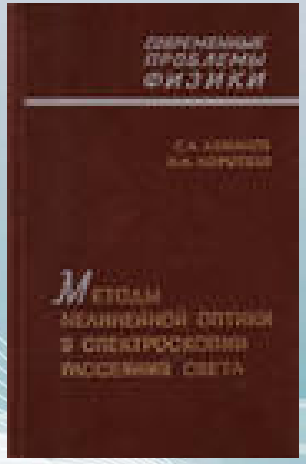
Public recognition of the scintific school of R.V. Khokhlov and S.A. Akhmanov

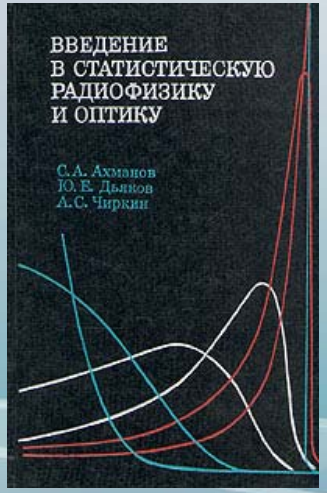
Russian Federation President Prize in the field of education

L.V. Keldysh, V.A. Makarov, V.V. Mikhaylin (with Yu.V. Kopaev, I.N. Zavestovskaya, V.N. Ochkin, L.P. Presniakov, V.F. Elesin, T.V.Marinina, V.P.Shorin)

2004 “For the training of high quality specialists, new scientific and educational technologies”

2011 will be fiftieth anniversary of laser nonlinear optics



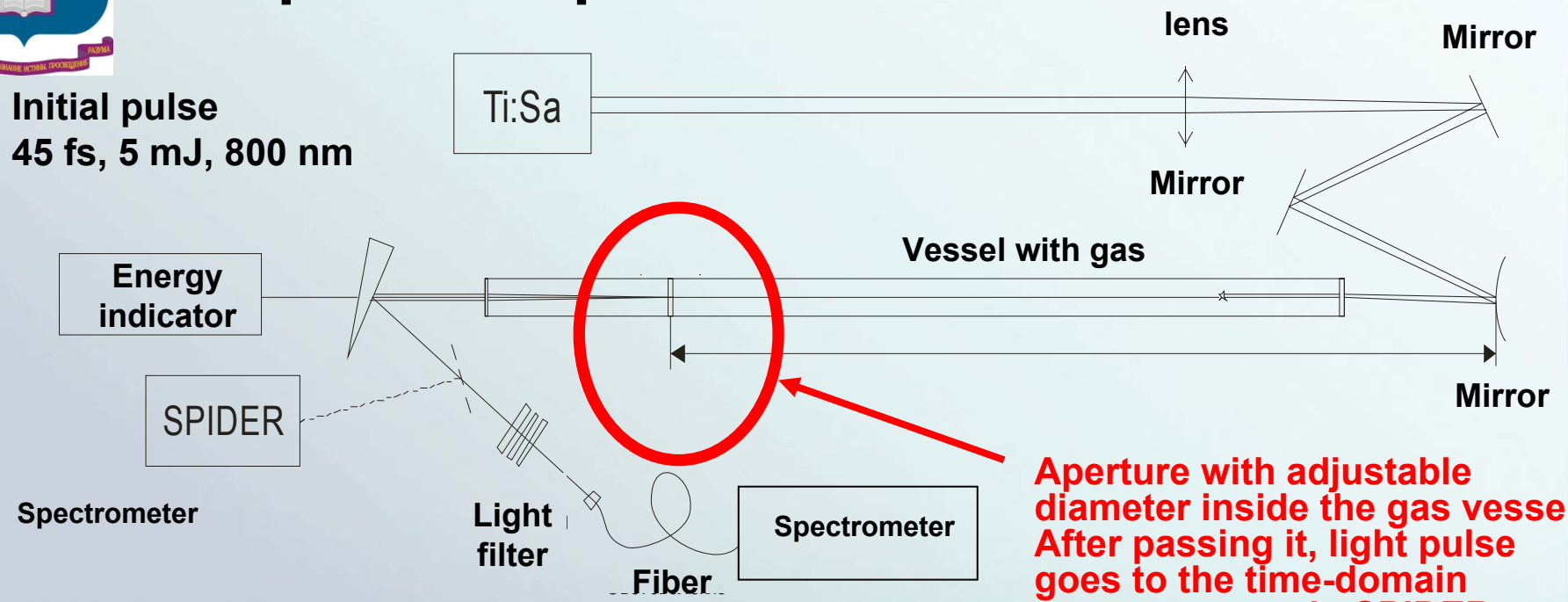


International Conferences on Coherent and Nonlinear Optics

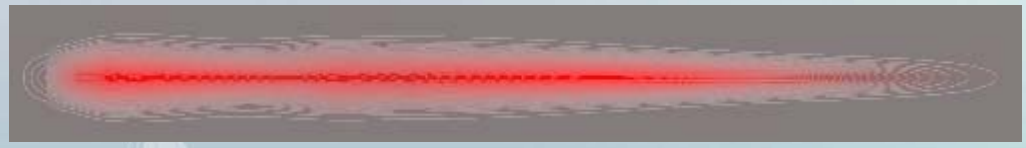
Research areas

- Fundamental problems of laser radiation interaction with matter
- Nonlinear laser spectroscopy and optical diagnostics
- Quantum optics
- Wave propagation in nonlinear medium and atmosphere
- Laser optoacoustic
- Laser biophysics, chemistry and biomedicine
- Physics of superstrong light fields
- Nonlinear polarizational optics
- Laser acoustics and nonlinear acoustics
- Femto- and nanotechnologies
- Terahertz optics
- Adaptive optics and systems with optical feedback
- Photonic crystal and microstructured fiber optics

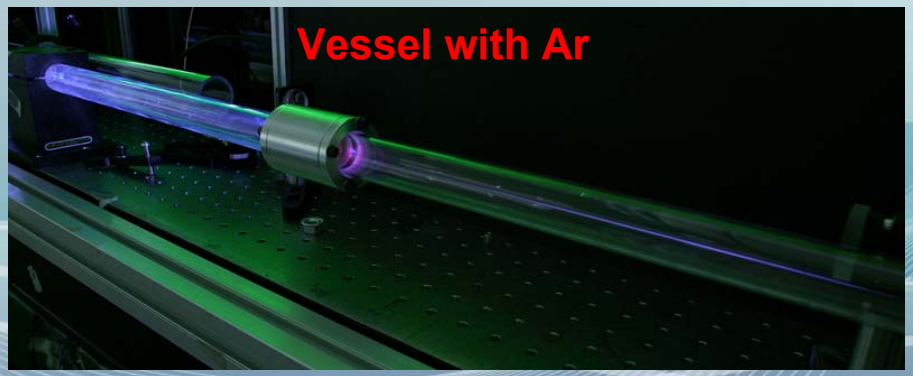
Self-compression of the light pulse during the spatio-temporal localization in filament

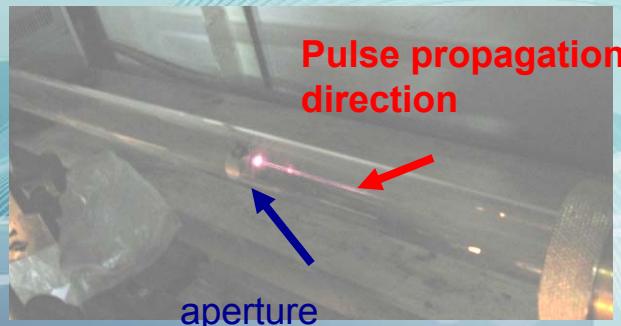


Aperture with adjustable diameter inside the gas vessel. After passing it, light pulse goes to the time-domain measurements in SPIDER

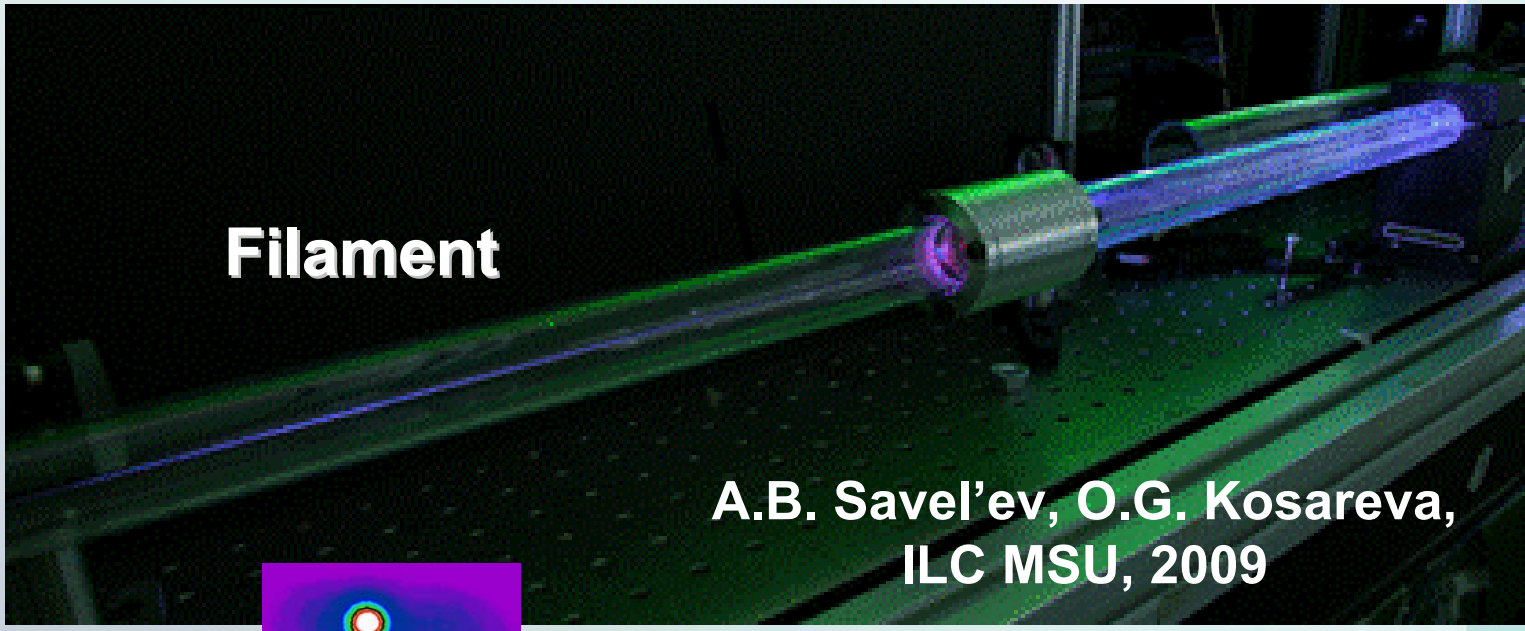


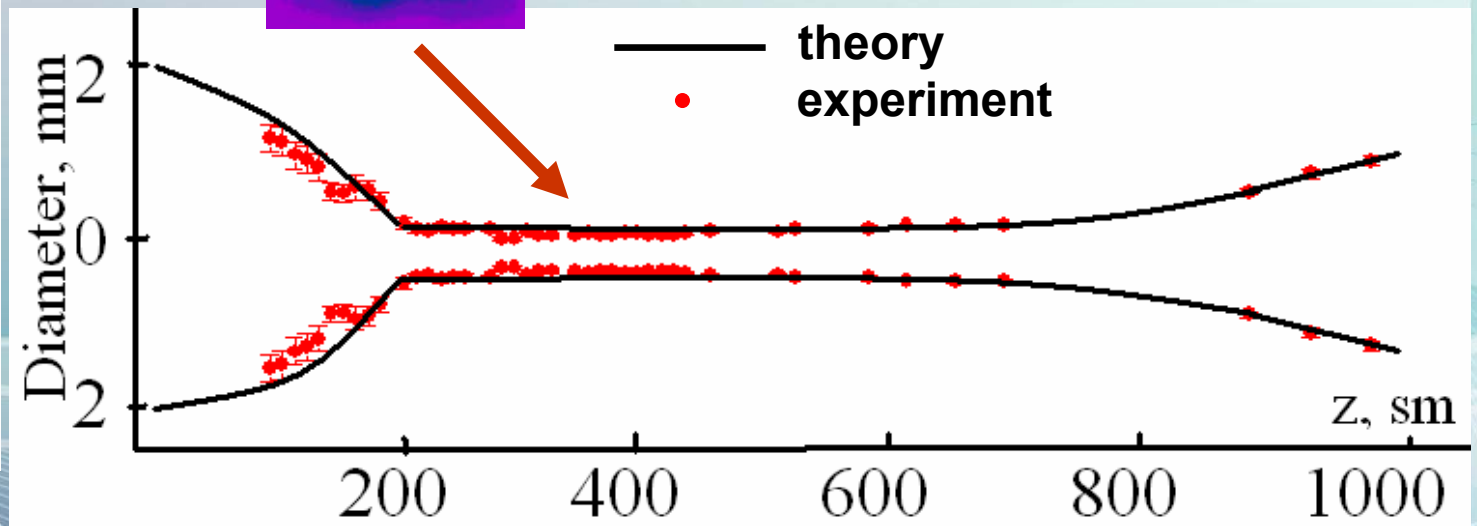
Professor
A.B. Savel'ev



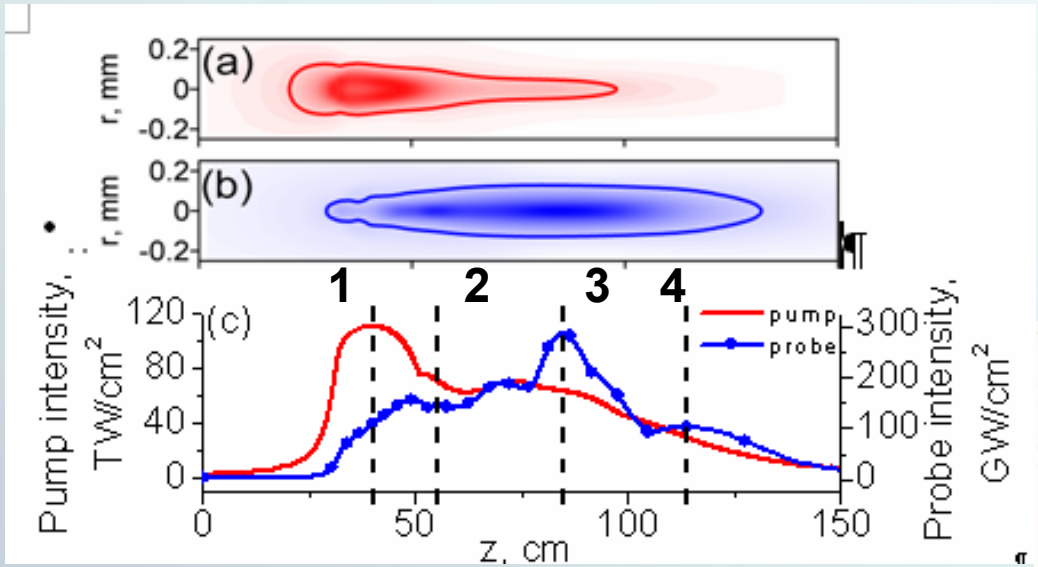


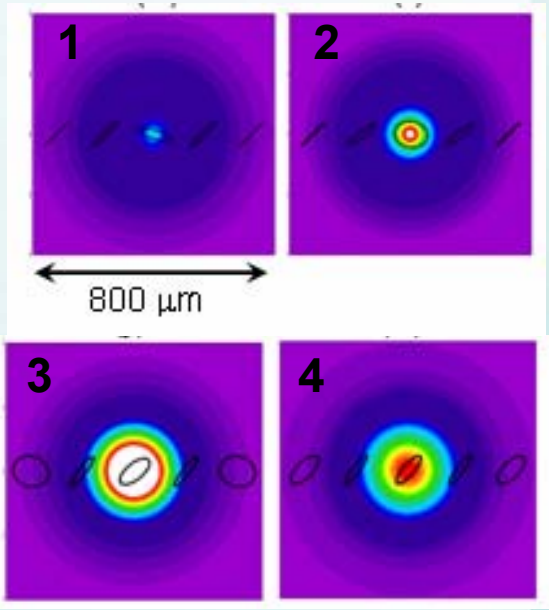
Filamentation of femtosecond laser pulses

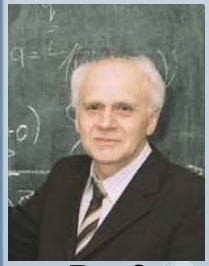




Propagation of powerful femtosecond light pulses distances in atmosphere



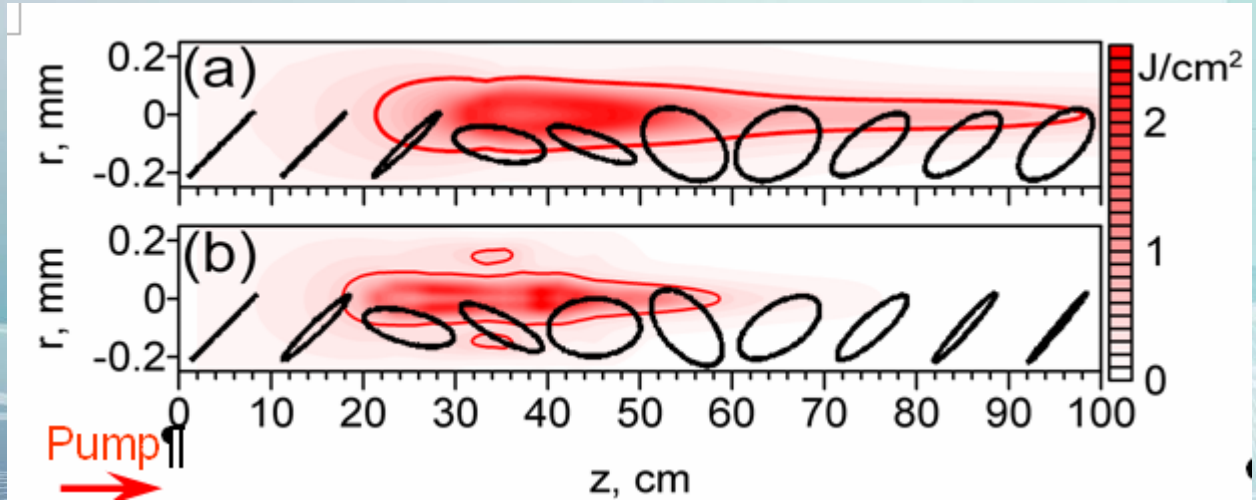




Prof.
V.P.Kandidov

Associate prof.
O.G.Kosareva

Associate prof.
S.A.Shlenov



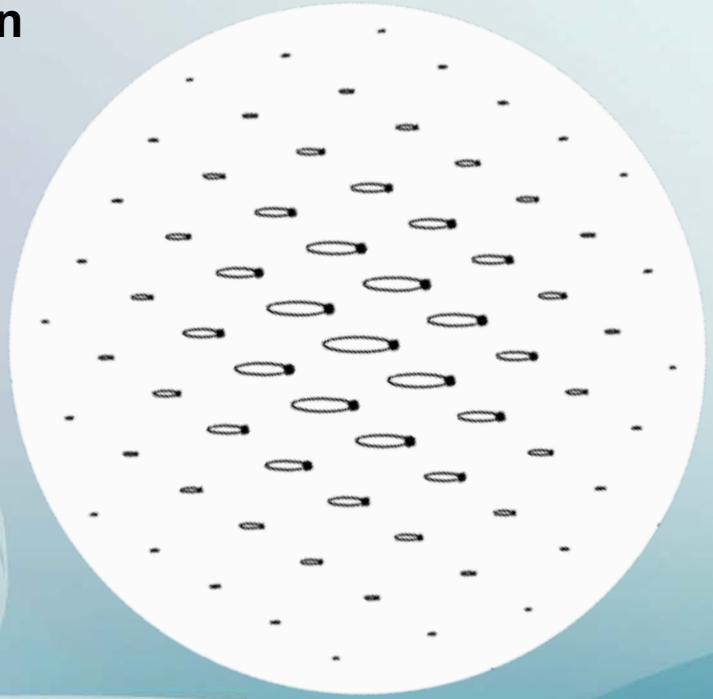
Nonlinear polarization optics

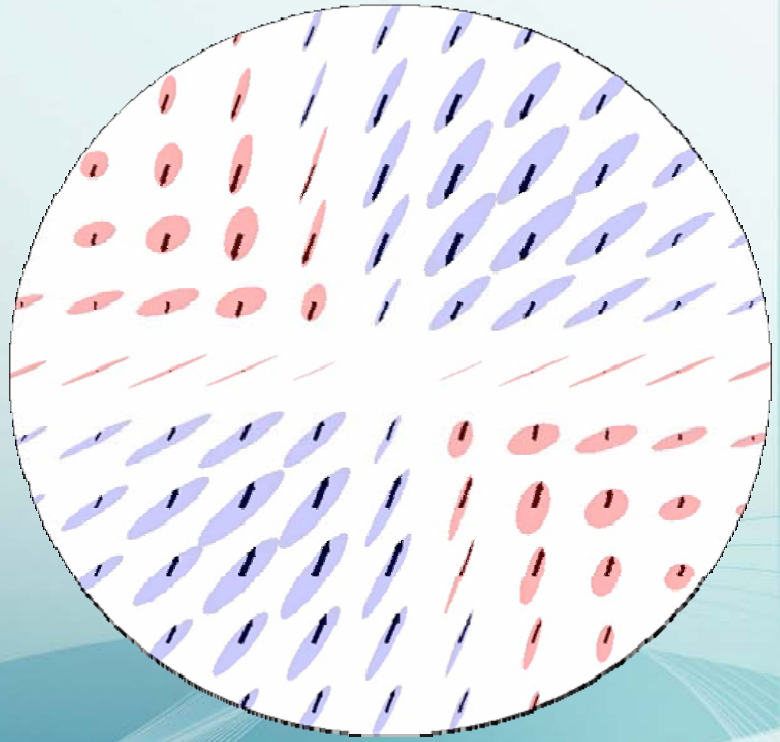
Incident Gaussian beam at ω frequency

The beam at 2ω frequency reflected from chiral surface

Right circular polarization

Left circular polarization

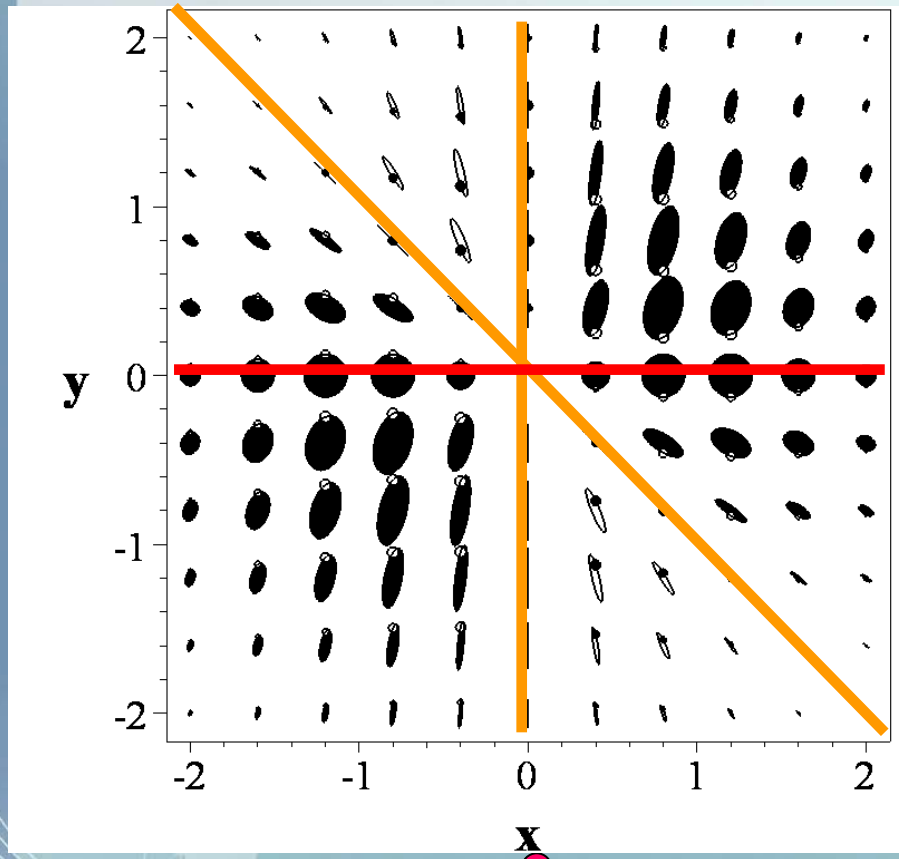


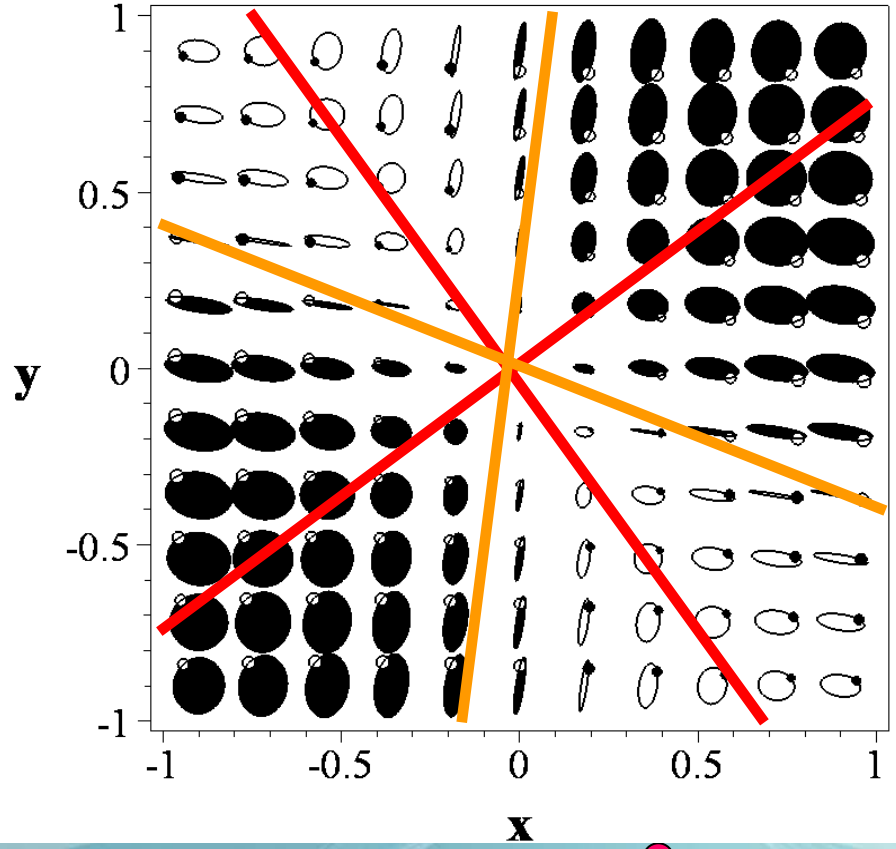


V.A.Makarov, I.A.Perezhogin, 2006, 2009

Singular nonlinear polarization optics

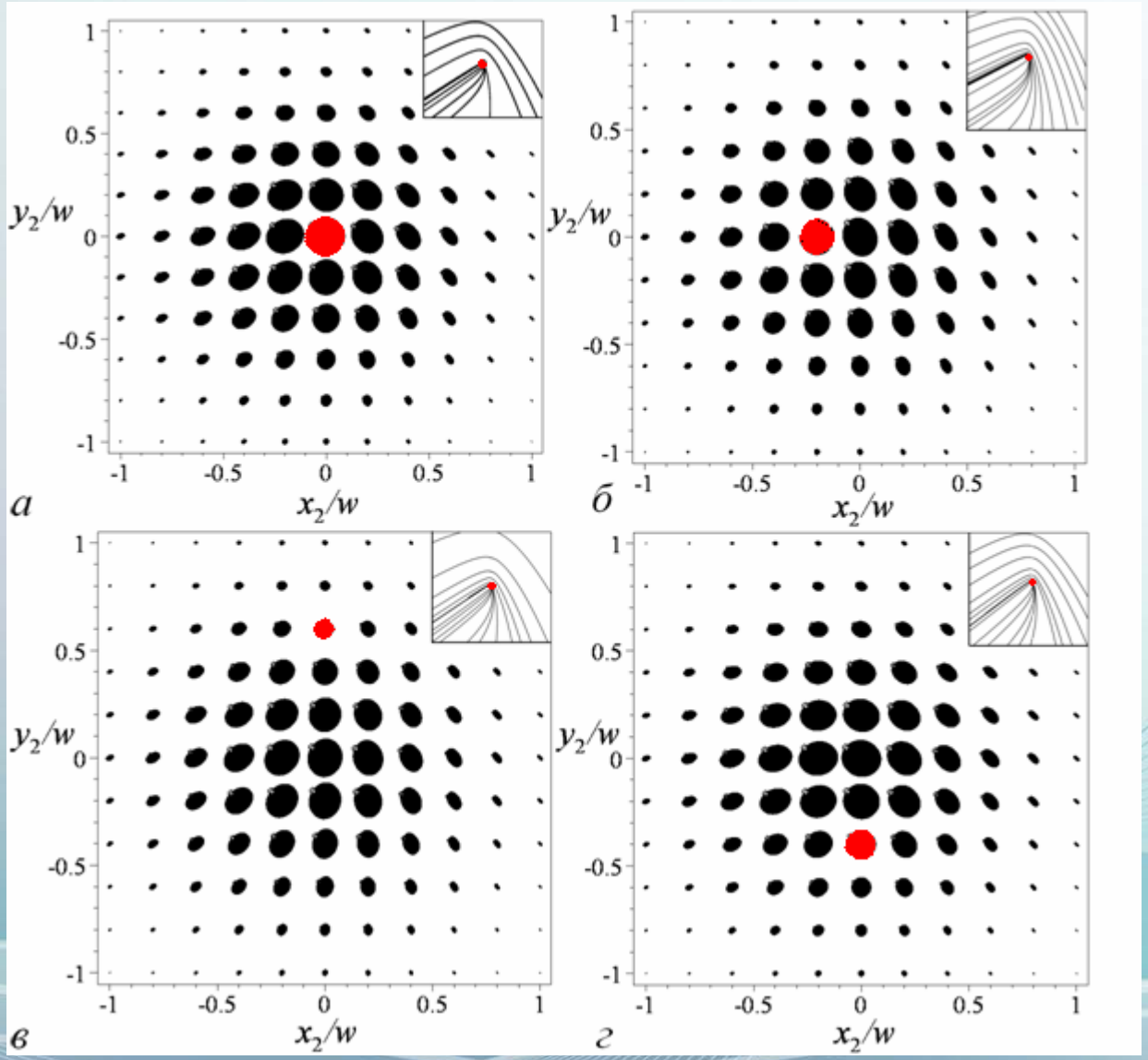
Cross-section of reflected beam at sum frequency (normal incidence)





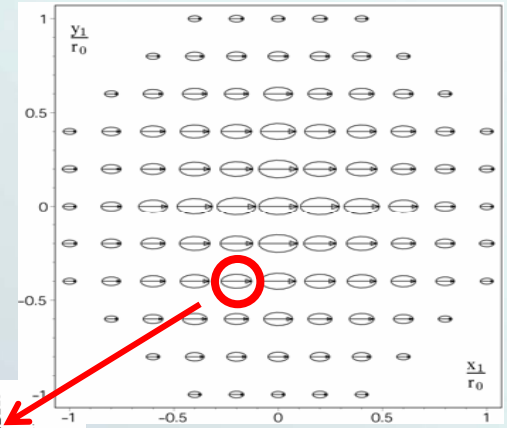
$M = -1$ $\quad -1 < M < 0$ $\quad M = 0$ $\quad 0 < M < 1$ $\quad M = 1$

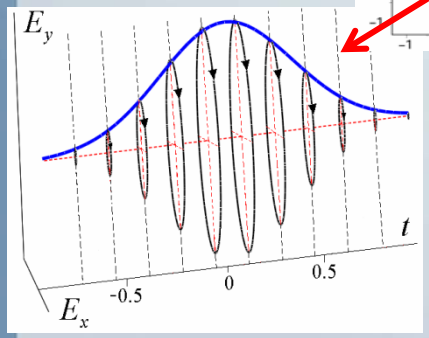
C-point of ‘lemon’ type in cross-section of second harmonic beam



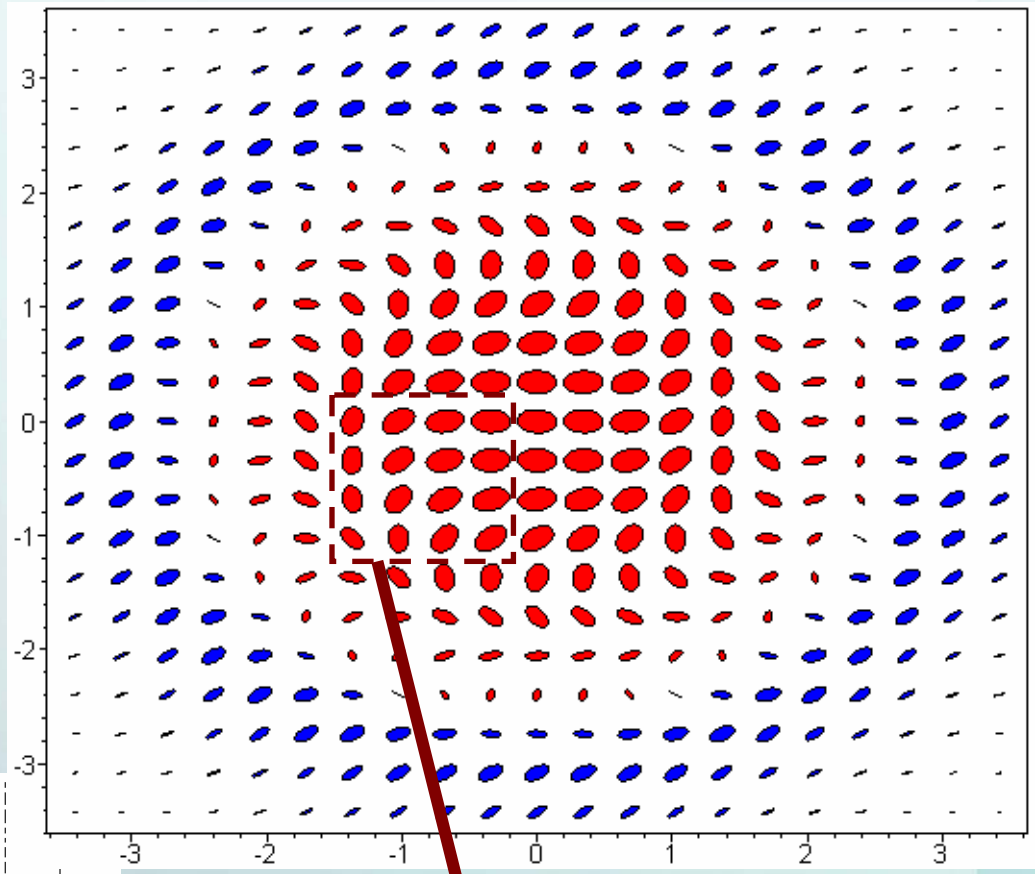
Light at the end of chiral medium

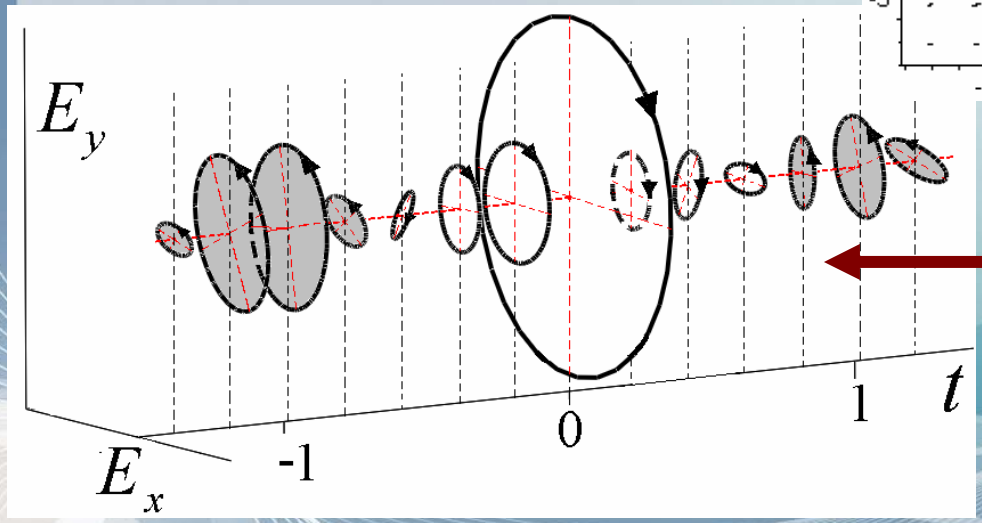
$z = 0$

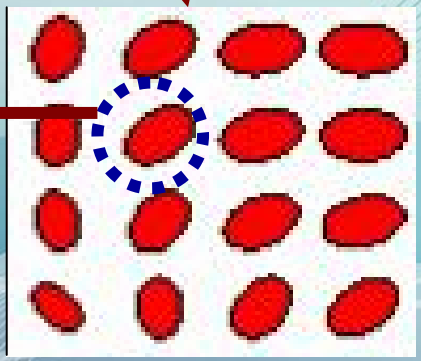




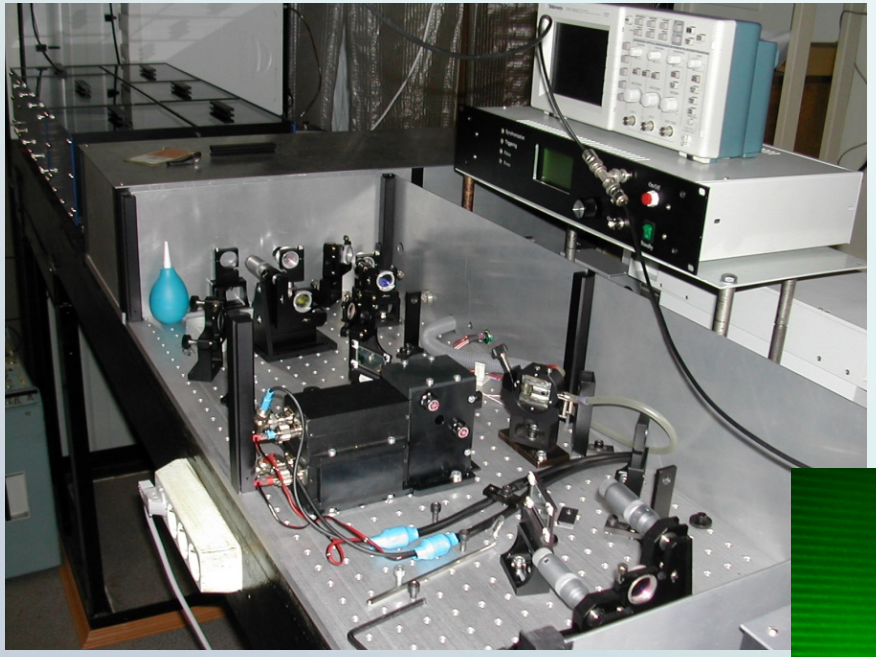
$z = L$







Femtosecond pulses of superstrong light field: physics of matter under extreme conditions

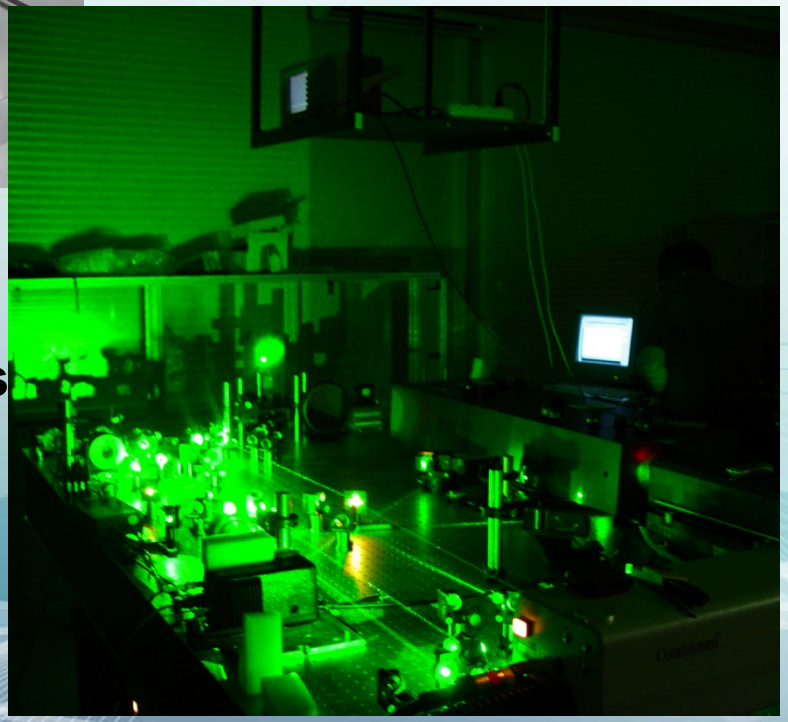


- Generation of supershort pulses in IR, visible and UV
- Interaction of femtosecond pulses with plasma of modified targets

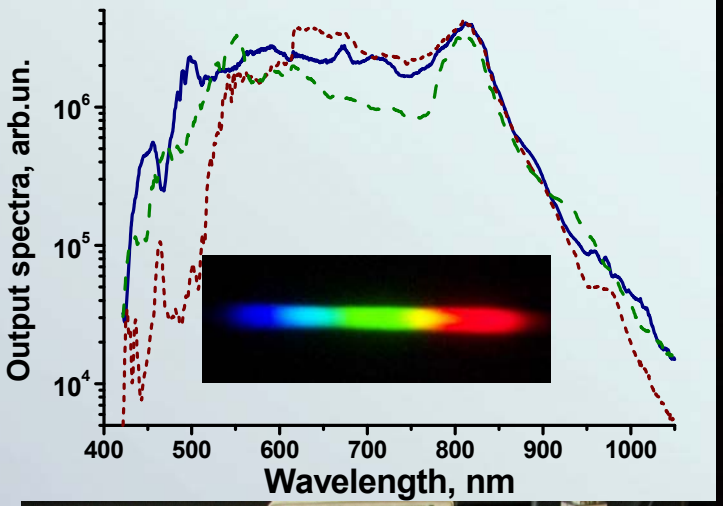
Professor
V.M. Gordienko

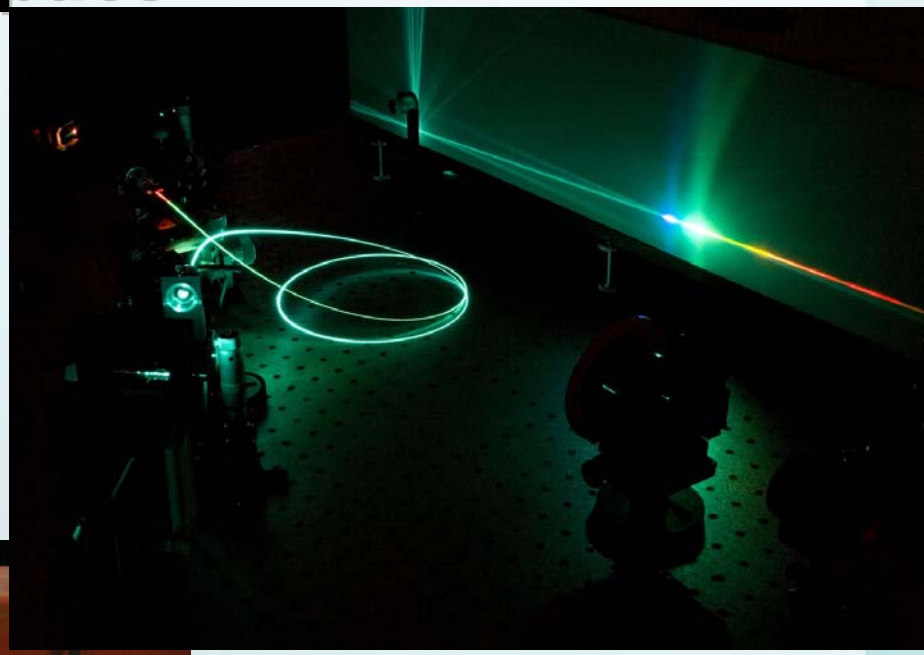
Professor
A.B. Savel'ev

- It was shown at the first time, that the excitation of low-energy nuclear levels is possible in case of interaction of femtosecond laser pulse with intensity 10^{17}W/cm^2 with target.

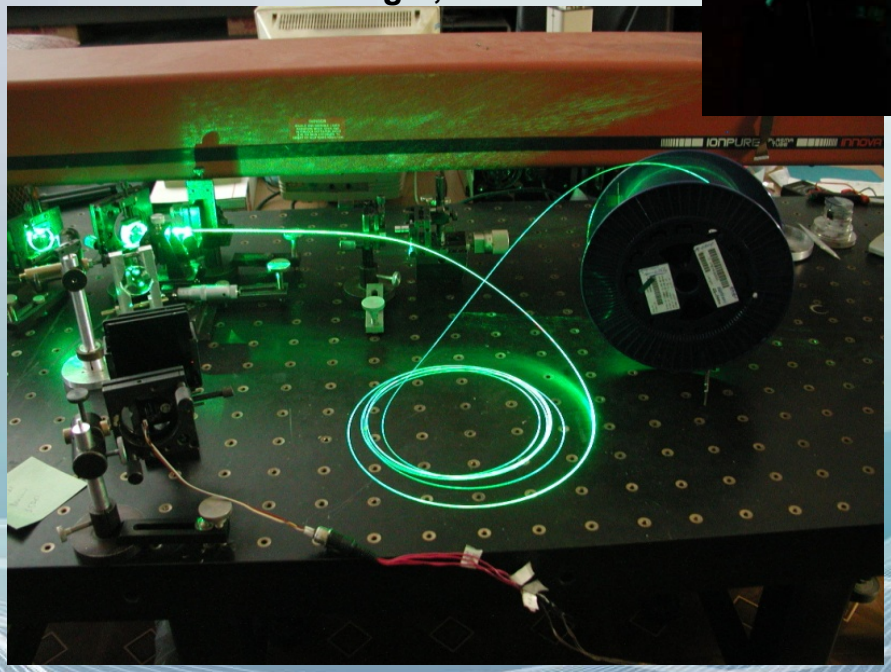


Photonic crystal and microstructured fiber optics





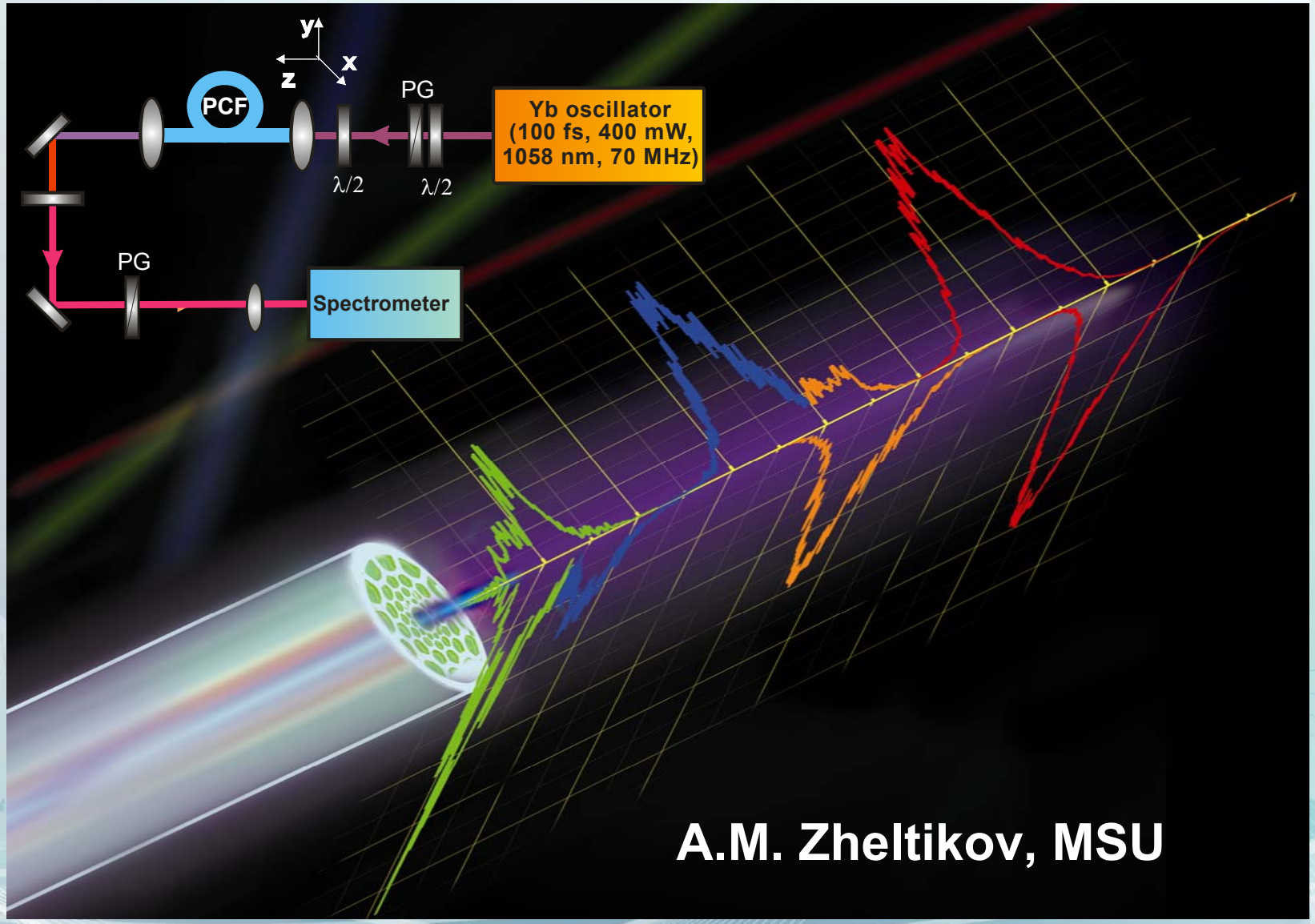
Prof.
A.M.Zheltikov



Associate prof.
A.B.Fedotov

A.M. Zheltikov, Microstructured fiber optics (2004)

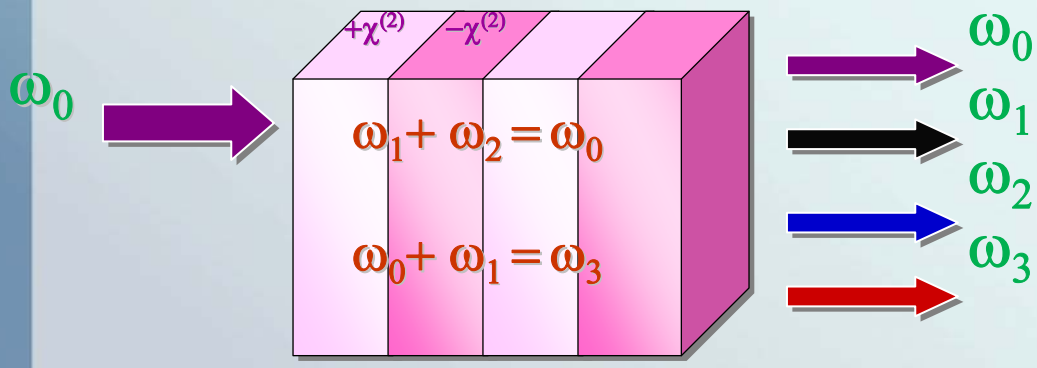
Solitons with different polarization in nonisotropic microstructured fibers



A.M. Zheltikov, MSU

Parametric generation into the ultraviolet range

Serial interactions

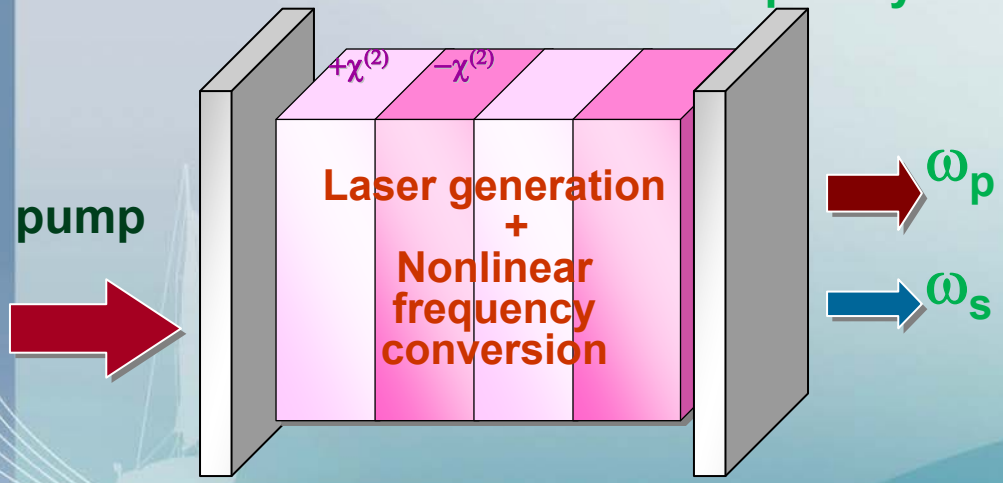


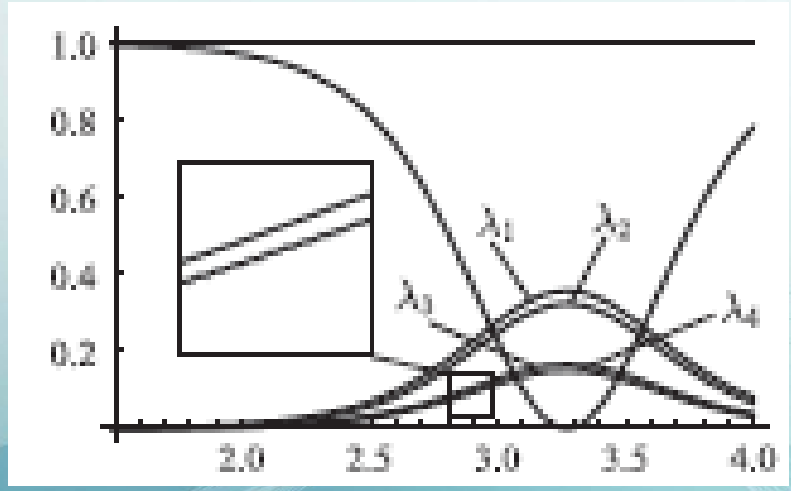
$$\omega_1 + \omega_2 = \omega_p,$$

$$\omega_1 + \omega_p = \omega_3,$$

$$\omega_2 + \omega_p = \omega_4.$$

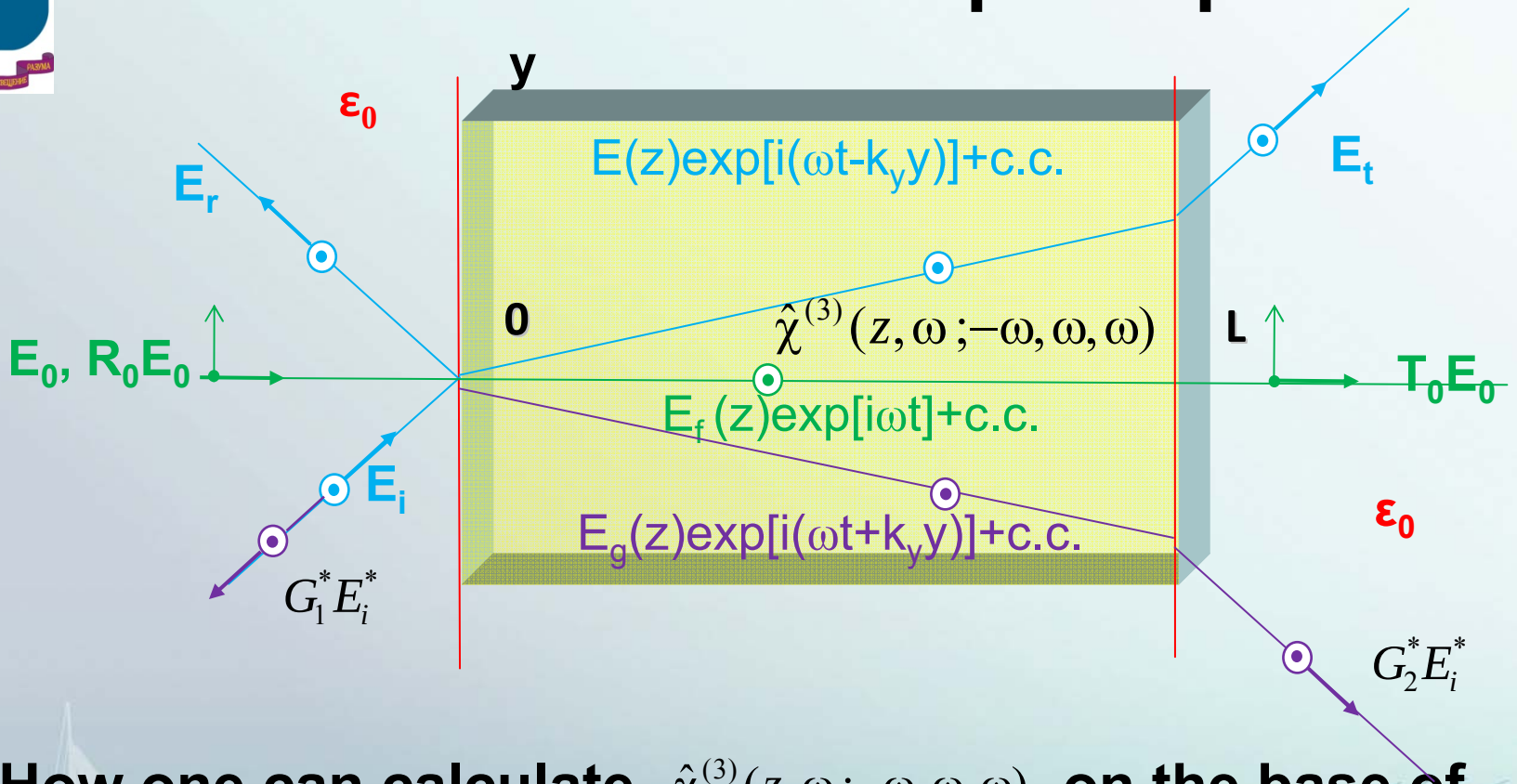
Self-conversion of laser frequency





A.S. Chirkin, MSU, 2009

The inverse nonlinear optical problem



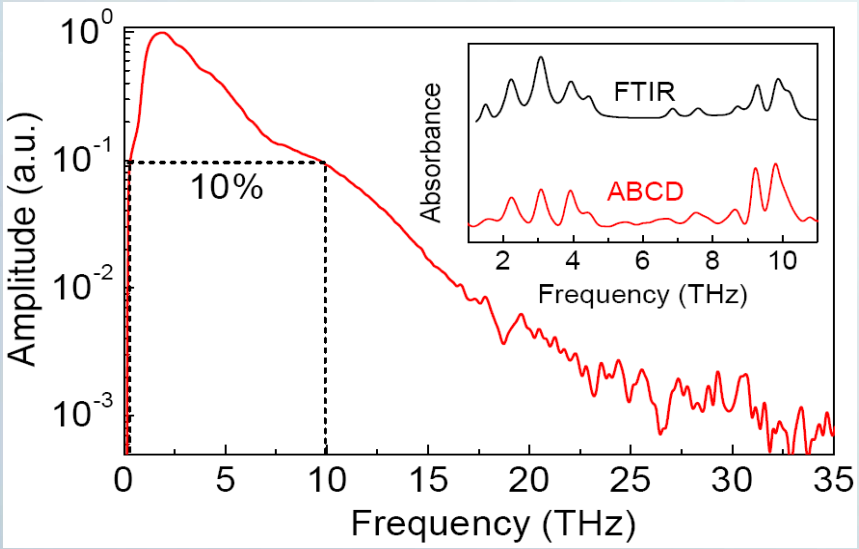
1. How one can calculate $\hat{\chi}^{(3)}(z,\omega;-\omega,\omega,\omega)$ on the base of known parameters all reflected and transmitted waves?

2. How many solutions does this problem have?

A.A.Golubkov, V.A.Makarov, 2010

THz spectroscopy and matter diagnostics

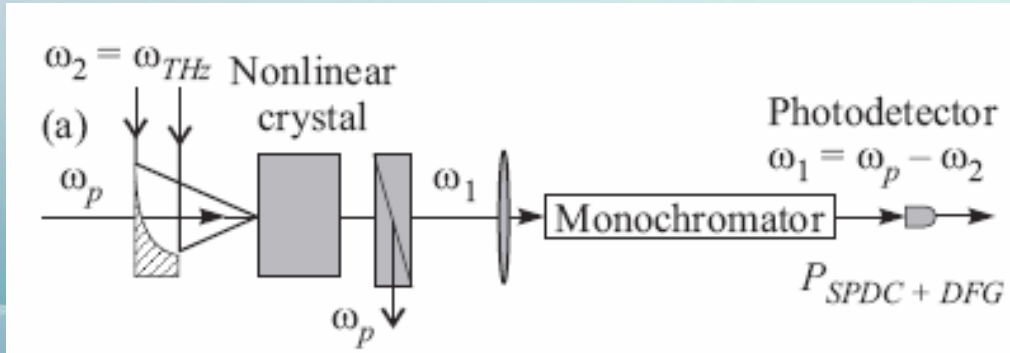
$$E_{THz}(t) \propto \chi_{eff}^{(3)} E_{2\omega}(t) E^*_{\omega}(t) E^*_{\omega}(t) \cos(\phi)$$



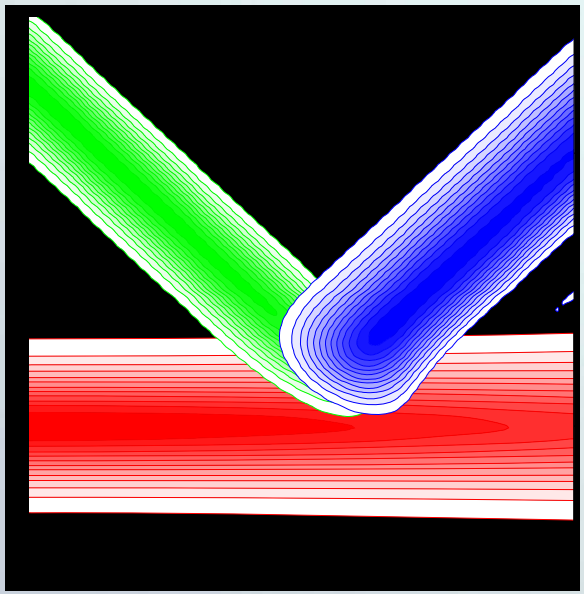
Professor
A.N. Penin

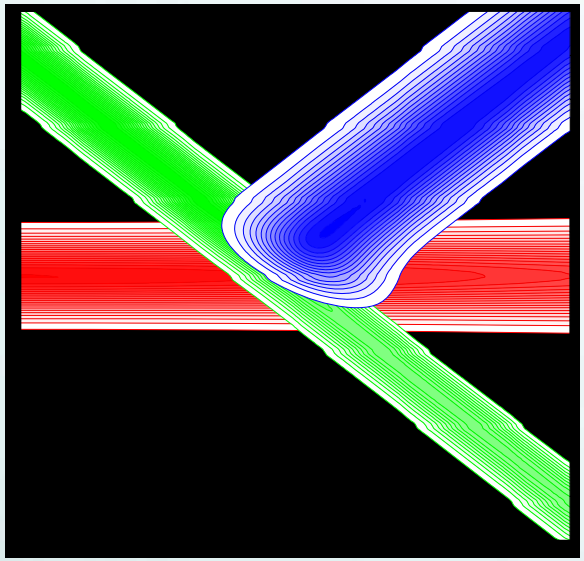
Associate
professor
A.P. Shkurinov

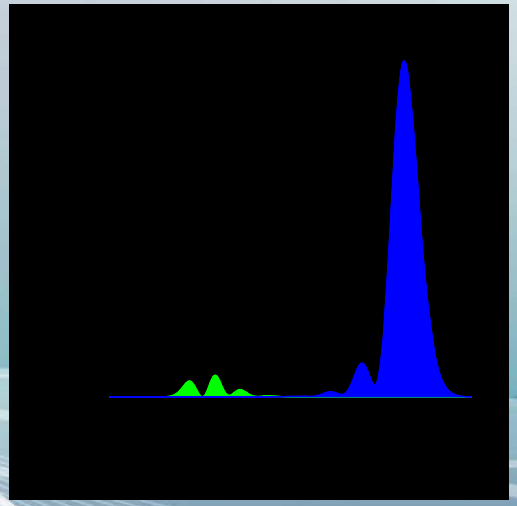
Dr.Sci.
G.Kh. Kitaeva

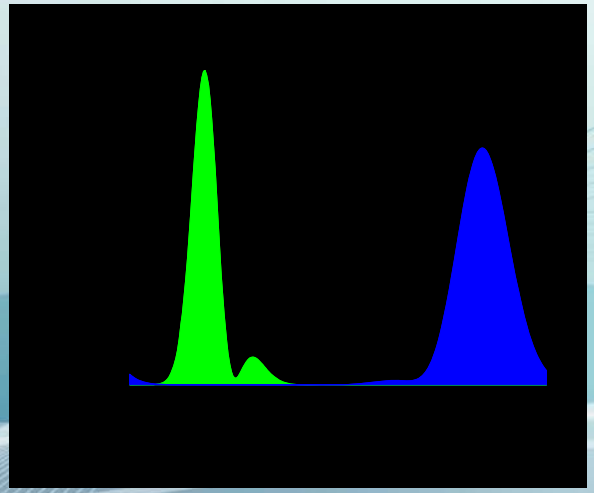


Parametric switching in three-frequency synchronic interactions









THANK YOU FOR YOUR ATTENTION!