Tr

John Dudley @johnmdudley

Dec 6, 2021 • 44 tweets • johnmdudley/status/1467761727525822467

To kick off the week, here is an updated (and long!) thread on the history of nonlinear optics. First a real surprise! The explicit use of the terminology "nonlinear optics" can be traced back to Erwin Schrödinger in 1942. Yes you read that right. Schrödinger himself!

Proceedings of the Royal Irish Academy.

NON-LINEAR OPTICS.

By ERWIN SCHRÖDINGER.

[From the Dublin Institute for Advanced Studies.]

[Read January 26. Published June 24, 1942.]

Table of Contents.

1. *Report on method followed and results obtained.*

This paper is to be the first of a series in which the non-linear electrodynamics, proposed by Born about seven years ago,[1] and developed by Born and Infeld[2] and others, is to be resumed with the hope that it might after all provide an escape from the "infinities" which, starting from the classical concept of a Maxwellian point-singularity, haunt present day quantum-conceptions of photons, electrons, protons and mesons at every

[1] M. Born, Proc. Roy. Soc. (A), **143**, 410, 1934.
[2] M. Born and L. Infeld, *ibid.*, **144**, 425, 1934.

Non-Linear Optics
Author(s): Erwin Schrödinger
Source: *Proceedings of the Royal Irish Academy. Section A: Mathematical and Physical Sciences*, 1941/1942, Vol. 47 (1941/1942), pp. 77-117
Published by: Royal Irish Academy

A New Exact Solution in Non-Linear Optics (Two-Wave-System)
Author(s): Erwin Schrödinger
Source: *Proceedings of the Royal Irish Academy. Section A: Mathematical and Physical Sciences*, Vol. 49 (1943/1944), pp. 59-66
Published by: Royal Irish Academy

Although this paper isn't really what we would describe today as non-linear optics. Rather it describes "vacuum light-light scattering" or nonlinear QED. But the wording Schrödinger used definitely sounds familiar! It builds on earlier work by Born, Infeld, Euler.

The next section will show that *three* waves do produce a fourth one classically, provided that between the three propagation vectors *a certain condition* is at least approximately fulfilled.

But if $\nu'_4 - \nu_4$ *is* small—which means that a fourth wave is possible, together with which the three given waves very nearly fulfil what in quantum-theory is called the conservation of energy and momentum.

It is significant that in the approximate formulae (obtained from (5, 3) just by omitting a dash)

$$\begin{aligned} \nu_1 + \nu_2 &= \nu_3 + \nu_4 \\ \mathfrak{k}_1 + \mathfrak{k}_2 &= \mathfrak{k}_3 + \mathfrak{k}_4 \end{aligned} \qquad (5,12)$$

the ν's can have either sign and that the directions of propagation are indicated not by the $\mathfrak{k}_l$ but by the $\nu_l \mathfrak{k}_l / |\nu_l|$.

M. Born. On the quantum theory of the electromagnetic field Proc. R. Soc. Lond. **A143** 410–437 (1934)
M. Born & L. Infeld. Foundations of the new field theory. Proc. R. Soc. Lond. **A144** 425–451 (1934)
H. Euler. Über die Streuung von Licht an Licht nach der Diracschen Theorie. Ann. Phys. **418** 398-448 (1936)

It seems that what Schrödinger and the others were describing was finally observed in 2019 at @CERN @ATLASexperiment Can @jonmbutterworth confirm ?

ATLAS observes light scattering off light

New result studies photons interacting at high energies

17 March 2019 | By ATLAS Collaboration

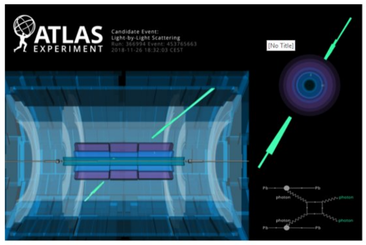


Figure 1: ATLAS event display showing the energy deposits of two photons in the electromagnetic calorimeter (green) on opposite sides and no other activity in the detector, which is the clean signature of light-by-light scattering. The Feynman diagram of this process is shown in the lower right corner. (Image: ATLAS Collaboration/CERN)

PHYSICAL REVIEW LETTERS **123**, 052001 (2019)

Observation of Light-by-Light Scattering in Ultraperipheral Pb + Pb Collisions with the ATLAS Detector

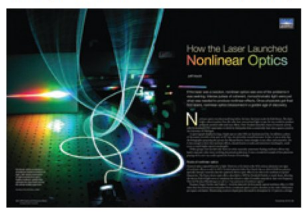
G. Aad *et al.*[*]
(ATLAS Collaboration)

(Received 11 April 2019; published 31 July 2019)

[1] H. Euler and B. Köckel, The scattering of light by light in Dirac's theory, Naturwissenschaften **23**, 246 (1935).
[2] W. Heisenberg and H. Euler, Consequences of Dirac's theory of positrons, Z. Phys. **98**, 714 (1936).
[3] I. F. Ginzburg and A. Schiller, Search for a heavy magnetic monopole at the Fermilab Tevatron and CERN LHC, Phys. Rev. D **57**, R6599 (1998).
[4] S. Fichet, G. von Gersdorff, B. Lenzi, C. Royon, and M. Saimpert, Light-by-light scattering with intact protons at the LHC: From standard model to new physics, J. High Energy Phys. 02 (2015) 165.
[5] S. Knapen, T. Lin, H. K. Lou, and T. Melia, Searching for Axionlike Particles with Ultraperipheral Heavy-Ion Collisions, Phys. Rev. Lett. **118**, 171801 (2017).
[6] M. Bauer, M. Neubert, and A. Thamm, Collider probes of axion-like particles, J. High Energy Phys. 12 (2017) 044.
[7] J. Ellis, N. E. Mavromatos, and T. You, Light-by-Light Scattering Constraint on Born-Infeld Theory, Phys. Rev. Lett. **118**, 261802 (2017).

Thanks to Dr George Nemes & Prof Svetlana Lukishova for highlighting this early work to the optics community! In fact George Nemes wrote to @OPNmagazine in 2010 after @jeffhecht wrote his great historical article for the 50th laser anniversary. https://www.optica-opn.org/home/articles/volume_22/issue_4/departments/letters/letters/

How the Laser Launched Nonlinear Optics



It was a great pleasure to read Jeff Hecht's interesting historical article, "How the Laser Launched Nonlinear Optics" (OPN Nov. 2010). It recalled for me my early attempts to understand and organize the field of nonlinear optics as a young researcher by "deciphering" its basics and tracking its history. I did this in Romania during the late 1960s, and my efforts resulted in the first Romanian book on nonlinear optics (*Introduction to Nonlinear Optics,* Romanian Academy Publishers, Bucharest).

I would like to make two comments: one addition and one correction to Hecht's paper. The addition refers to the section on the roots of nonlinear optics, and more specifically to when the term "nonlinear optics" was first introduced. The paper mentions that the Soviet scientist Vavilov introduced the term in 1944. This might be very well true for an experimental nonlinear optical effect. However, in 1942 and 1943, Erwin Schrödinger published two theoretical papers in which the name "nonlinear optics" is explicitly used in the title (Proc. Royal Irish Academy **47** A, 77-117, 1942 and Proc. Royal Irish Academy **49** A, 59-66, 1943).

The correction is related to the section on Soviet research and optical parametric oscillators. Hecht states that the Soviets made their first OPO using a KTP ($KTiOPO_4$, potassium titanyl phosphate) nonlinear crystal. I believe this is a printing error, and the crystal was almost surely KDP (KH_2PO_4, potassium dihydrogen phosphate). The KTP crystal became available much later, in the late 1970s and early 1980s, while the KDP crystal was among the most popular nonlinear crystals in the 1960s and afterwards.

Thanks for allowing me to make these comments. I continue to enjoy historical articles on optical subjects published in OPN and also to follow the fascinating evolution of the optics and laser field today.

George Nemes
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THE AUTHOR RESPONDS: I want to thank George Nemes for tracing the term "nonlinear optics" back further than I was able to. I also want to express my gratitude to him for spotting my error in saying that the early Russian OPOs were made with KTP. When I checked an early English-language review of Russian parametric oscillator research, it listed KDP as the material used in the early Russian work (A.G. Akmanov et al. IEEE J. Quantum Electron. QE-4, **11**, 828, 1968). My apologies for the mistake.

Jeff Hecht
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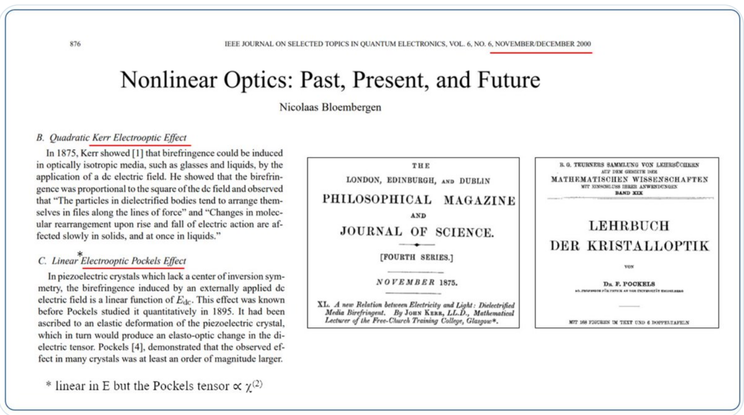
jeff@jeffhecht.com

(Aside: I just met George Nemes this month - so I thought! In an absolutely crazy coincidence, as a student in 1991, I had attended the [@ictpnews]() Winter College on Ultrafast Phenomena at the same time as him and we are about 1 m apart in the group photo.)

As a general question, how well-known are the early days of nonlinear optics? How far back does it go? For example, there are many effects considered part of nonlinear optics today that pre-date the laser. A non-exhaustive list could include some of these 19th century precursors.



876 IEEE JOURNAL ON SELECTED TOPICS IN QUANTUM ELECTRONICS, VOL. 6, NO. 6, NOVEMBER/DECEMBER 2000

Nonlinear Optics: Past, Present, and Future

Nicolaas Bloembergen

B. Quadratic Kerr Electrooptic Effect

In 1875, Kerr showed [1] that birefringence could be induced in optically isotropic media, such as glasses and liquids, by the application of a dc electric field. He showed that the birefringence was proportional to the square of the dc field and observed that "The particles in dielectrified bodies tend to arrange themselves in files along the lines of force" and "Changes in molecular rearrangement upon rise and fall of electric action are affected slowly in solids, and at once in liquids."

C. Linear Electrooptic Pockels Effect*

In piezoelectric crystals which lack a center of inversion symmetry, the birefringence induced by an externally applied dc electric field is a linear function of E_{dc}. This effect was known before Pockels studied it quantitatively in 1895. It had been ascribed to an elastic deformation of the piezoelectric crystal, which in turn would produce an elasto-optic change in the dielectric tensor. Pockels [4], demonstrated that the observed effect in many crystals was at least an order of magnitude larger.

THE LONDON, EDINBURGH, AND DUBLIN PHILOSOPHICAL MAGAZINE AND JOURNAL OF SCIENCE. [FOURTH SERIES.] NOVEMBER 1875.

XL. *A new Relation between Electricity and Light: Dielectrified Media Birefringent. By* JOHN KERR, *LL.D., Mathematical Lecturer of the Free-Church Training College, Glasgow*.*

B. G. TEUBNERS SAMMLUNG VON LEHRBÜCHERN AUF DEM GEBIETE DER MATHEMATISCHEN WISSENSCHAFTEN MIT EINSCHLUSS IHRER ANWENDUNGEN BAND XIX

LEHRBUCH DER KRISTALLOPTIK

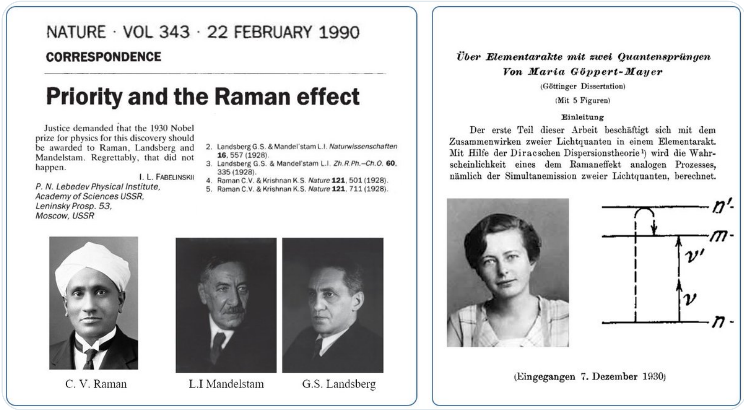
VON

DR. F. POCKELS

MIT 168 FIGUREN IM TEXT UND 6 DOPPELTAFELN

* linear in E but the Pockels tensor $\propto \chi^{(2)}$

We could also include the Raman effect and Goeppert-Mayer's theory of Two Photon Absorption. Note that there was controversy about the award of the 1930 Nobel Prize only to Raman because Mandelstam & Landsberg had seen the same effect one week earlier in 1928!


NATURE · VOL 343 · 22 FEBRUARY 1990

CORRESPONDENCE

Priority and the Raman effect

Justice demanded that the 1930 Nobel prize for physics for this discovery should be awarded to Raman, Landsberg and Mandelstam. Regrettably, that did not happen.

I. L. FABELINSKII

P. N. Lebedev Physical Institute, Academy of Sciences USSR, Leninsky Prosp. 53, Moscow, USSR

2. Landsberg G.S. & Mandel'stam L.I. *Naturwissenschaften* **16**, 557 (1928).
3. Landsberg G.S. & Mandel'stam L.I. *Zh.R.Ph.–Ch.O.* **60**, 335 (1928).
4. Raman C.V. & Krishnan K.S. *Nature* **121**, 501 (1928).
5. Raman C.V. & Krishnan K.S. *Nature* **121**, 711 (1928).

C. V. Raman L.I Mandelstam G.S. Landsberg

Über Elementarakte mit zwei Quantensprüngen

Von Maria Göppert-Mayer

(Göttinger Dissertation)

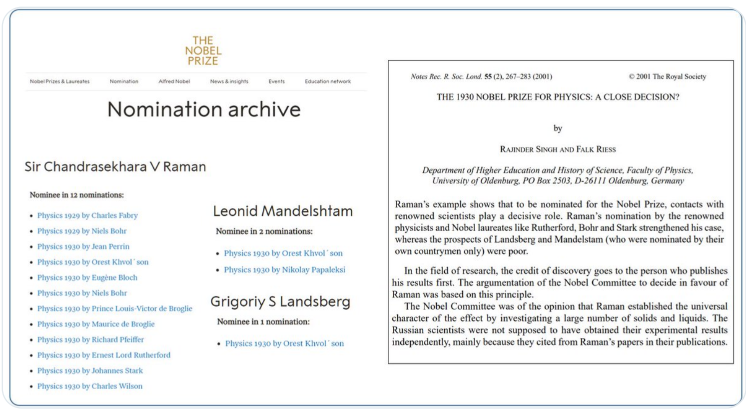
(Mit 5 Figuren)

Einleitung

Der erste Teil dieser Arbeit beschäftigt sich mit dem Zusammenwirken zweier Lichtquanten in einem Elementarakt. Mit Hilfe der Diracschen Dispersionstheorie [1]) wird die Wahrscheinlichkeit eines dem Ramaneffekt analogen Prozesses, nämlich der Simultanemission zweier Lichtquanten, berechnet.

(Eingegangen 7. Dezember 1930)

A decisive factor in the @NobelPrize award seems to be Raman's nomination by major physicists & former laureates from around the world. Mandelstam and Landsberg had support from a much more limited community! You can read more about this in the article by Singh & Reiss.


THE NOBEL PRIZE

Nobel Prizes & Laureates Nomination Alfred Nobel News & insights Events Education network

Nomination archive

Sir Chandrasekhara V Raman

Nominee in 12 nominations:

- Physics 1929 by Charles Fabry
- Physics 1929 by Niels Bohr
- Physics 1930 by Jean Perrin
- Physics 1930 by Orest Khvol´son
- Physics 1930 by Eugène Bloch
- Physics 1930 by Niels Bohr
- Physics 1930 by Prince Louis-Victor de Broglie
- Physics 1930 by Maurice de Broglie
- Physics 1930 by Richard Pfeiffer
- Physics 1930 by Ernest Lord Rutherford
- Physics 1930 by Johannes Stark
- Physics 1930 by Charles Wilson

Leonid Mandelshtam

Nominee in 2 nominations:

- Physics 1930 by Orest Khvol´son
- Physics 1930 by Nikolay Papaleksi

Grigoriy S Landsberg

Nominee in 1 nomination:

- Physics 1930 by Orest Khvol´son

Notes Rec. R. Soc. Lond. **55** (2), 267–283 (2001) © 2001 The Royal Society

THE 1930 NOBEL PRIZE FOR PHYSICS: A CLOSE DECISION?

by

RAJINDER SINGH AND FALK RIESS

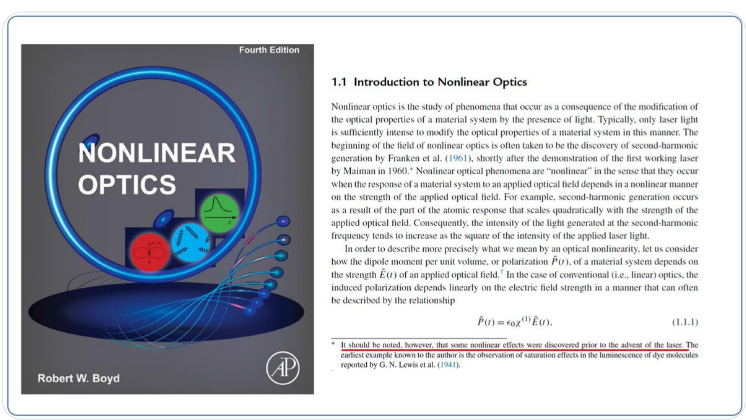
Department of Higher Education and History of Science, Faculty of Physics, University of Oldenburg, PO Box 2503, D-26111 Oldenburg, Germany

Raman's example shows that to be nominated for the Nobel Prize, contacts with renowned scientists play a decisive role. Raman's nomination by the renowned physicists and Nobel laureates like Rutherford, Bohr and Stark strengthened his case, whereas the prospects of Landsberg and Mandelstam (who were nominated by their own countrymen only) were poor.

In the field of research, the credit of discovery goes to the person who publishes his results first. The argumentation of the Nobel Committee to decide in favour of Raman was based on this principle.

The Nobel Committee was of the opinion that Raman established the universal character of the effect by investigating a large number of solids and liquids. The Russian scientists were not supposed to have obtained their experimental results independently, mainly because they cited from Raman's papers in their publications.

Aside from these earlier studies, many sources trace the first experiments in nonlinear optics as we understand it today to 1941. Indeed, the seminal text by @BoydNLOLab cites the experiments of Gilbert Lewis in 1941.



1.1 Introduction to Nonlinear Optics

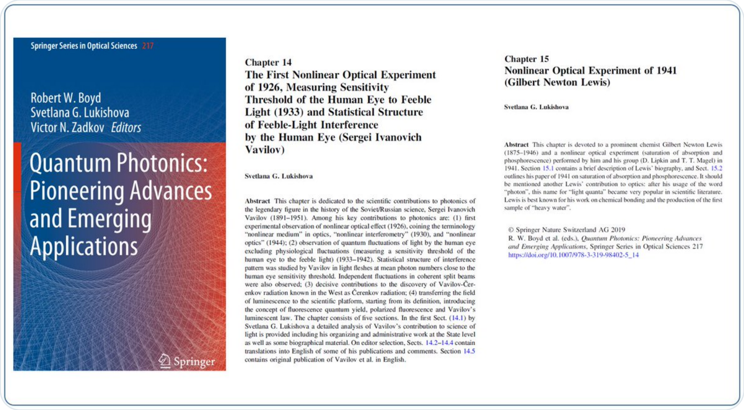
Nonlinear optics is the study of phenomena that occur as a consequence of the modification of the optical properties of a material system by the presence of light. Typically, only laser light is sufficiently intense to modify the optical properties of a material system in this manner. The beginning of the field of nonlinear optics is often taken to be the discovery of second-harmonic generation by Franken et al. (1961), shortly after the demonstration of the first working laser by Maiman in 1960.* Nonlinear optical phenomena are "nonlinear" in the sense that they occur when the response of a material system to an applied optical field depends in a nonlinear manner on the strength of the applied optical field. For example, second-harmonic generation occurs as a result of the part of the atomic response that scales quadratically with the strength of the applied optical field. Consequently, the intensity of the light generated at the second-harmonic frequency tends to increase as the square of the intensity of the applied laser light.

In order to describe more precisely what we mean by an optical nonlinearity, let us consider how the dipole moment per unit volume, or polarization $\tilde{P}(t)$, of a material system depends on the strength $\tilde{E}(t)$ of an applied optical field.† In the case of conventional (i.e., linear) optics, the induced polarization depends linearly on the electric field strength in a manner that can often be described by the relationship

$$\tilde{P}(t) = \epsilon_0 \chi^{(1)} \tilde{E}(t), \quad (1.1.1)$$

* It should be noted, however, that some nonlinear effects were discovered prior to the advent of the laser. The earliest example known to the author is the observation of saturation effects in the luminescence of dye molecules reported by G. N. Lewis et al. (1941).

This book from 2019 gives a more detailed history, with Prof Lukishova pointing out not only the experiments of Gilbert Lewis (1941) but the much earlier work of Sergei Ivanovich Vavilov and V.L. Levshin (1926), including commentary and reprints of original papers.



Chapter 14
The First Nonlinear Optical Experiment of 1926, Measuring Sensitivity Threshold of the Human Eye to Feeble Light (1933) and Statistical Structure of Feeble-Light Interference by the Human Eye (Sergei Ivanovich Vavilov)

Svetlana G. Lukishova

Abstract This chapter is dedicated to the scientific contributions to photonics of the legendary figure in the history of the Soviet/Russian science, Sergei Ivanovich Vavilov (1891–1951). Among his key contributions to photonics are: (1) first experimental observation of nonlinear optical effect (1926), coining the terminology "nonlinear medium" in optics, "nonlinear interferometry" (1930), and "nonlinear optics" (1944); (2) observation of quantum fluctuations of light by the human eye excluding physiological fluctuations (measuring a sensitivity threshold of the human eye to the feeble light) (1933–1942). Statistical structure of interference pattern was studied by Vavilov in light fleshes at mean photon numbers close to the human eye sensitivity threshold. Independent fluctuations in coherent split beams were also observed; (3) decisive contributions to the discovery of Vavilov-Čerenkov radiation known in the West as Čerenkov radiation; (4) transferring the field of luminescence to the scientific platform, starting from its definition, introducing the concept of fluorescence quantum yield, polarized fluorescence and Vavilov's luminescent law. The chapter consists of five sections. In the first Sect. (14.1) by Svetlana G. Lukishova a detailed analysis of Vavilov's contribution to science of light is provided including his organizing and administrative work at the State level as well as some biographical material. On editor selection, Sects. 14.2–14.4 contain translations into English of some of his publications and comments. Section 14.5 contains original publication of Vavilov et al. in English.

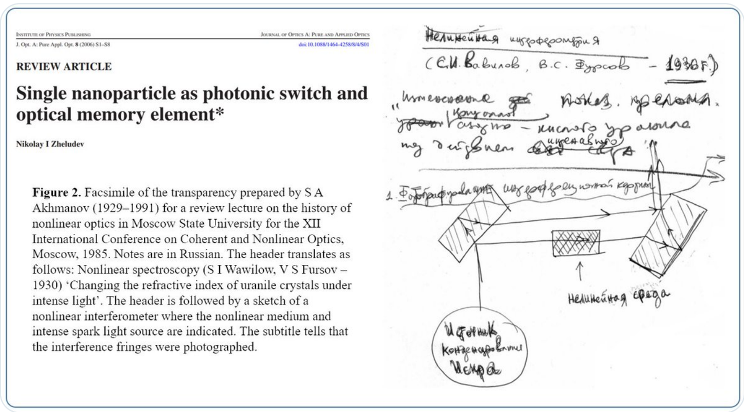
Chapter 15
Nonlinear Optical Experiment of 1941 (Gilbert Newton Lewis)

Svetlana G. Lukishova

Abstract This chapter is devoted to a prominent chemist Gilbert Newton Lewis (1875–1946) and a nonlinear optical experiment (saturation of absorption and phosphorescence) performed by him and his group (D. Lipkin and T. T. Magel) in 1941. Section 15.1 contains a brief description of Lewis' biography, and Sect. 15.2 outlines his paper of 1941 on saturation of absorption and phosphorescence. It should be mentioned another Lewis' contribution to optics: after his usage of the word "photon", this name for "light quanta" became very popular in scientific literature. Lewis is best known for his work on chemical bonding and the production of the first sample of "heavy water".

© Springer Nature Switzerland AG 2019
R. W. Boyd et al. (eds.), *Quantum Photonics: Pioneering Advances and Emerging Applications*, Springer Series in Optical Sciences 217
https://doi.org/10.1007/978-3-319-98402-5_14

The experiment of Vavilov was described by Akhmanov during his 1985 review lecture on the history of nonlinear optics at Moscow State University for the XII ICONO Conference. Akhmanov's figure was reproduced in a 2006 paper by Nikolay Zheludev @orctweets



INSTITUTE OF PHYSICS PUBLISHING — JOURNAL OF OPTICS A: PURE AND APPLIED OPTICS
J. Opt. A: Pure Appl. Opt. **8** (2006) S1–S8 — doi:10.1088/1464-4258/8/4/S01

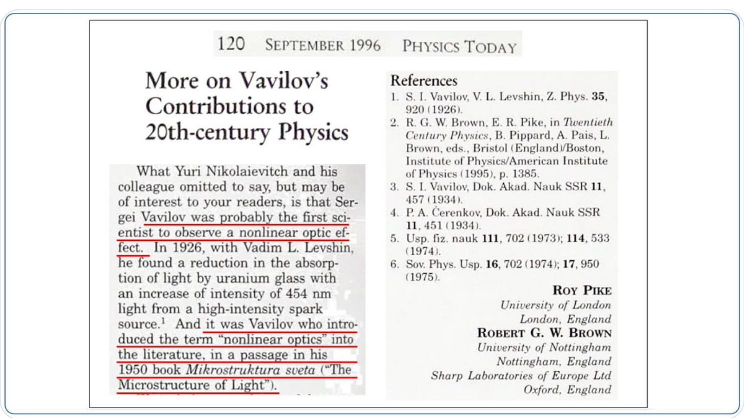
REVIEW ARTICLE

Single nanoparticle as photonic switch and optical memory element*

Nikolay I Zheludev

Figure 2. Facsimile of the transparency prepared by S A Akhmanov (1929–1991) for a review lecture on the history of nonlinear optics in Moscow State University for the XII International Conference on Coherent and Nonlinear Optics, Moscow, 1985. Notes are in Russian. The header translates as follows: Nonlinear spectroscopy (S I Wawilow, V S Fursov – 1930) 'Changing the refractive index of uranile crystals under intense light'. The header is followed by a sketch of a nonlinear interferometer where the nonlinear medium and intense spark light source are indicated. The subtitle tells that the interference fringes were photographed.

Sergey Ivanovich Vavilov (1891-1951) was a giant of physics. His 1926 contributions to nonlinear optics were actually pointed out in @physicstoday in 1996.



120 SEPTEMBER 1996 PHYSICS TODAY

More on Vavilov's Contributions to 20th-century Physics

What Yuri Nikolaievitch and his colleague omitted to say, but may be of interest to your readers, is that Sergei Vavilov was probably the first scientist to observe a nonlinear optic effect. In 1926, with Vadim L. Levshin, he found a reduction in the absorption of light by uranium glass with an increase of intensity of 454 nm light from a high-intensity spark source.[1] And it was Vavilov who introduced the term "nonlinear optics" into the literature, in a passage in his 1950 book *Mikrostruktura sveta* ("The Microstructure of Light").

References

1. S. I. Vavilov, V. L. Levshin, Z. Phys. **35**, 920 (1926).
2. R. G. W. Brown, E. R. Pike, in *Twentieth Century Physics*, B. Pippard, A. Pais, L. Brown, eds., Bristol (England)/Boston, Institute of Physics/American Institute of Physics (1995), p. 1385.
3. S. I. Vavilov, Dok. Akad. Nauk SSR **11**, 457 (1934).
4. P. A. Čerenkov, Dok. Akad. Nauk SSR **11**, 451 (1934).
5. Usp. fiz. nauk **111**, 702 (1973); **114**, 533 (1974).
6. Sov. Phys. Usp. **16**, 702 (1974); **17**, 950 (1975).

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Nottingham, England
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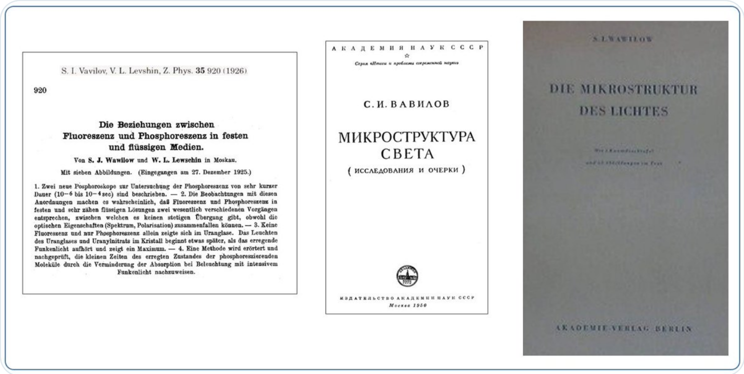
Oxford, England

Vavilov used the term "nonlinear optics" in his 1950 book (translated in German in 1954) & was co-discoverer of Cherenkov radiation (Vavilov-Cherenkov radiation in Russia). But he died before seeing maser/laser oscillation and before the 1958 Nobel Prize for Cherenkov radiation.



S. I. Vavilov, V. L. Levshin, Z. Phys. **35** 920 (1926)

920

Die Beziehungen zwischen Fluoreszenz und Phosphoreszenz in festen und flüssigen Medien.

Von **S. J. Wawilow** und **W. L. Lewschin** in Moskau.

Mit sieben Abbildungen. (Eingegangen am 27. Dezember 1925.)

1. Zwei neue Posphoroskope zur Untersuchung der Phosphoreszenz von sehr kurzer Dauer (10^{-6} bis 10^{-4} sec) sind beschrieben. — 2. Die Beobachtungen mit diesen Anordnungen machen es wahrscheinlich, daß Fluoreszenz und Phosphoreszenz in festen und sehr zähen flüssigen Lösungen zwei wesentlich verschiedenen Vorgängen entsprechen, zwischen welchen es keinen stetigen Übergang gibt, obwohl die optischen Eigenschaften (Spektrum, Polarisation) zusammenfallen können. — 3. Keine Fluoreszenz und nur Phosphoreszenz allein zeigte sich im Uranglase. Das Leuchten des Uranglases und Uranylnitrats im Kristall beginnt etwas später, als das erregende Funkenlicht aufhört und zeigt ein Maximum. — 4. Eine Methode wird erörtert und nachgeprüft, die kleinen Zeiten des erregten Zustandes der phosphoreszierenden Moleküle durch die Verminderung der Absorption bei Beleuchtung mit intensivem Funkenlicht nachzuweisen.

АКАДЕМИЯ НАУК СССР

С. И. ВАВИЛОВ

МИКРОСТРУКТУРА СВЕТА

(ИССЛЕДОВАНИЯ И ОЧЕРКИ)

ИЗДАТЕЛЬСТВО АКАДЕМИИ НАУК СССР

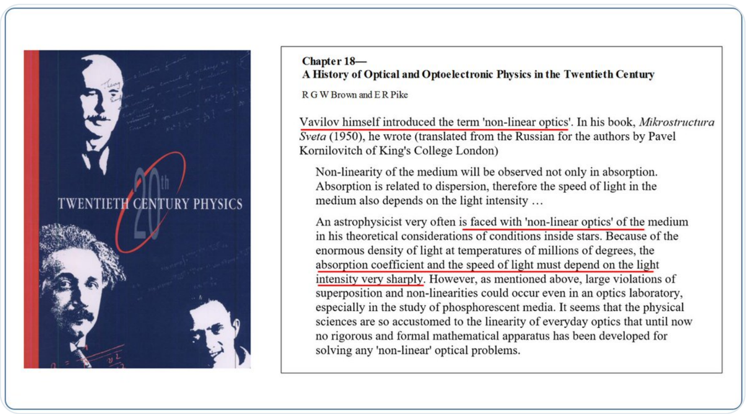
Москва 1950

S. I. WAWILOW

DIE MIKROSTRUKTUR DES LICHTES

AKADEMIE-VERLAG BERLIN

Brown & Pike give the translation of how he introduced nonlinear optics in a chapter in the wonderful book Twentieth Century Physics (Eds Brown, Abraham Pais, A. B. Pippard 1995). But we know now that Schrödinger had used the term even earlier!



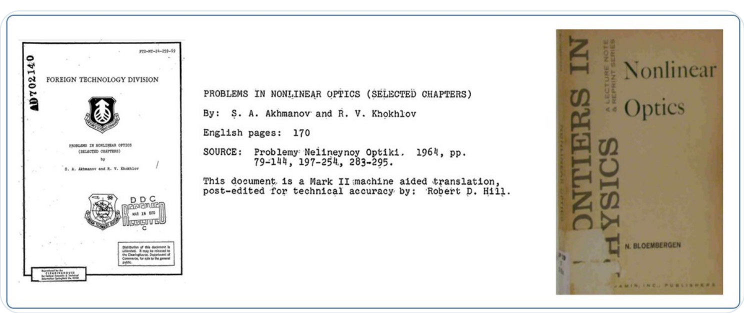
Chapter 18—
A History of Optical and Optoelectronic Physics in the Twentieth Century

R G W Brown and E R Pike

Vavilov himself introduced the term 'non-linear optics'. In his book, *Mikrostructura Sveta* (1950), he wrote (translated from the Russian for the authors by Pavel Kornilovitch of King's College London)

> Non-linearity of the medium will be observed not only in absorption. Absorption is related to dispersion, therefore the speed of light in the medium also depends on the light intensity …
>
> An astrophysicist very often is faced with 'non-linear optics' of the medium in his theoretical considerations of conditions inside stars. Because of the enormous density of light at temperatures of millions of degrees, the absorption coefficient and the speed of light must depend on the light intensity very sharply. However, as mentioned above, large violations of superposition and non-linearities could occur even in an optics laboratory, especially in the study of phosphorescent media. It seems that the physical sciences are so accustomed to the linearity of everyday optics that until now no rigorous and formal mathematical apparatus has been developed for solving any 'non-linear' optical problems.

By the way, after Vavilov's book appeared in 1950, monographs on nonlinear optics appeared in 1964 by Akhmanov & Khokhlov, and 1965 by Bloembergen. These are the first dedicated volumes on the subject as far as I know. Please reply (add screenshots) if you know of others.



AD702140

FOREIGN TECHNOLOGY DIVISION

PROBLEMS IN NONLINEAR OPTICS (SELECTED CHAPTERS)

by

S. A. Akhmanov and R. V. Khokhlov

DDC

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PROBLEMS IN NONLINEAR OPTICS (SELECTED CHAPTERS)

By:  S. A. Akhmanov and R. V. Khokhlov

English pages:  170

SOURCE:  Problemy Nelineynoy Optiki.  1964, pp.
         79-144, 197-254, 283-295.

This document is a Mark II machine aided translation,
post-edited for technical accuracy by:  Robert D. Hill.
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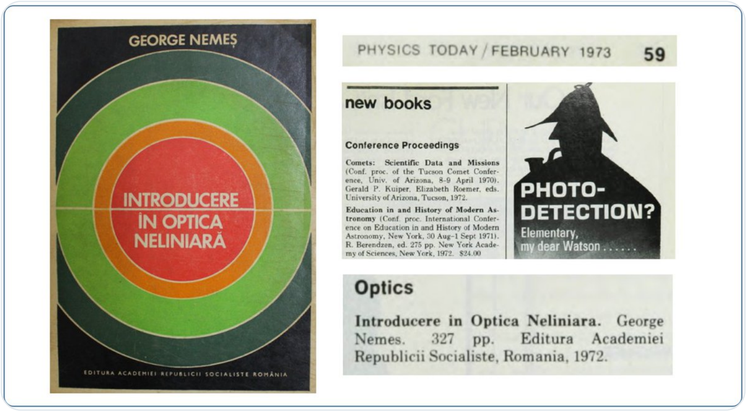
FRONTIERS IN PHYSICS

A LECTURE NOTE & REPRINT SERIES

Nonlinear Optics

N. BLOEMBERGEN

George Nemes also wrote one of the first books on nonlinear optics in 1972. Although published in Romanian, it was included in the New Books section of @PhysicsToday in Feb 1973. Nice ad for photodetectors as well.



Other early books on nonlinear optics include Butcher (1965), Baldwin (1969), and Zernike & Midwinter (1973). John Midwinter sadly passed away only very recently:

Polina Bayvel
@bayvel_p

Very sad to share the devastating news that our former Head of Department @ucleeenews and the true fibre-optics pioneer, Prof John E Midwinter FRS FREng, passed away. He led the research at BT enabling it to be the first in the world to introduce optical fibre into its network.

1:06 PM · Nov 17, 2021

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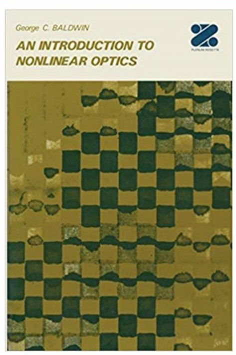
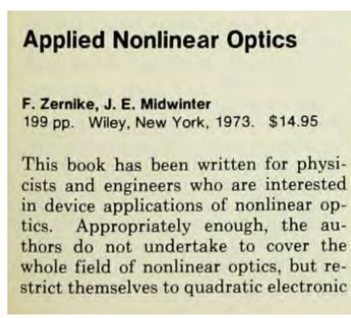
Tweet your reply





Applied Nonlinear Optics

F. Zernike, J. E. Midwinter
199 pp. Wiley, New York, 1973. $14.95

This book has been written for physicists and engineers who are interested in device applications of nonlinear optics. Appropriately enough, the authors do not undertake to cover the whole field of nonlinear optics, but restrict themselves to quadratic electronic

Self-focusing was of interest all around the world. Another early book was published in India in 1974. It was reviewed by Scottish soliton pioneer Willie Firth! @physicsscotland (There is in fact a separate thread on early books on nonlinear optics just waiting to be written!)

OPTICS AND LASER TECHNOLOGY . JUNE 1975

BOOKS

Self-focusing of laser beams in dielectrics, plasmas and semiconductors

M. S. Sodha, A. K. Ghatak, V. K. Tripathi
Tata McGraw-Hill, New Delhi, 1974 pp 149, £2.80

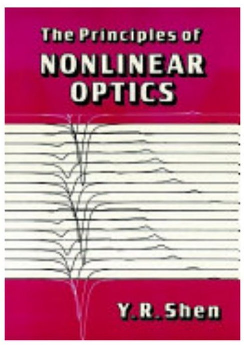
The book is rounded off with eight appendices and an enormous bibliography, useful because it covers literature from East and West Europe, and America.

Laser experimentalists would probably find the book too indigestible as an introduction to the subject, but those of theoretical bent with a reasonable grasp of the basic physics may well find the book useful, bearing in mind the excellent bibliography.

Finally, the Indian subsidiary of McGraw-Hill are to be congratulated on producing a book which is typographically excellent, hard bound and well laid out, all at a price which would hardly buy a single edition of a journal. At £2.80 the book must be recommended to anyone with more than a passing interest in the field.

W. J. Firth

A later 1984 book on nonlinear optics by Yuen-Ron Shen has become a classic. Its Introduction is legendary! Linearity beautifies, nonlinearity brings excitement and rejuvenation. Sounds about right to me!

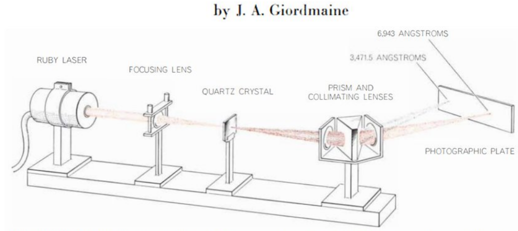


Physics would be dull and life most unfulfilling if all physical phenomena around us were linear. Fortunately, we are living in a nonlinear world. While linearization beautifies physics, nonlinearity provides excitement in physics. This book is devoted to the study of nonlinear electromagnetic phenomena in the optical region which normally occur with high-intensity laser beams. Nonlinear effects in electricity and magnetism have been known since Maxwell's time. Saturation of magnetization in a ferromagnet, electrical gas discharge, rectification of radio waves, and electrical characteristics of p–n junctions are just a few of the familiar examples. In the optical region, however, nonlinear optics became a subject of great common interest only after the laser was invented. It has since contributed a great deal to the rejuvenation of the old science of optics.

Going back in time again, a 1964 popular science article in Scientific American has become a remarkable work of major historical importance. Specifically, it describes the original second harmonic experiments of Franken et al. in some detail.

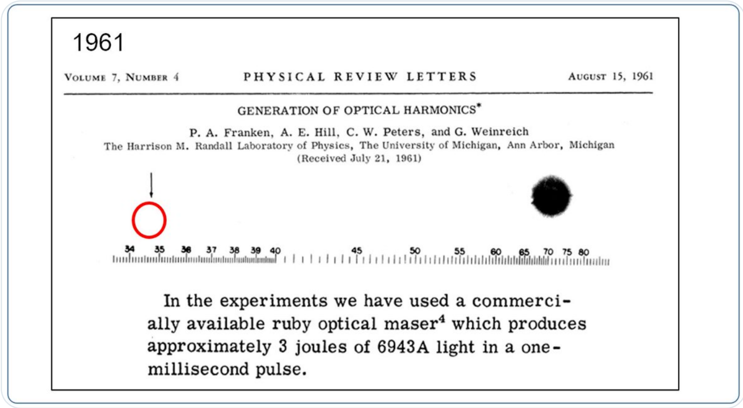
The Interaction of Light with Light

by J. A. Giordmaine

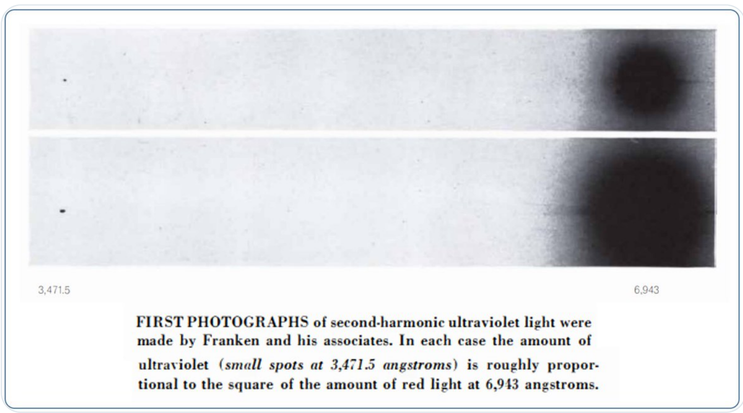


FIRST DEMONSTRATION that ultraviolet light could be generated by the intense flash of a ruby laser was made with this experimental arrangement in 1961 at the University of Michigan. The investigators were Peter A. Franken, Allen E. Hill, C. W. Peters and Gabriel Weinreich. The quartz crystal converted only a hundred-millionth of the incident light to ultraviolet light. On being passed through a prism the ultraviolet is bent more than the red laser light and the two can be photographed separately (*see below*).

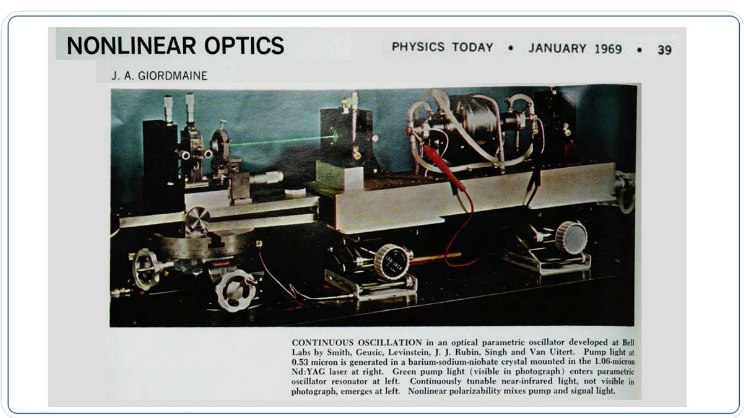
Remember the story about the 1961 Franken @PhysRevLett paper? The spectroscopic signature of the ruby laser second harmonic was edited out as a speck of dust! However, the Giordmaine paper from 1964 saved these results and showed the original plates!



So here we go! Remarkable! We finally see Franken's evidence for second harmonic generation! And it's easy to see why it was missed as a speck of dust. Maybe it's just me but I absolutely love the fact that we can finally see this SHG spot which has been missing for so long!



Giordmaine also wrote a great paper in @PhysicsToday in 1969 with fantastic colour pictures such as this early OPO. Clearly the adjustment knobs were cooler in those days! I think we still have one of those 1960s elevating jacks in our lab.



A great overview of post-laser Western & USSR-era nonlinear optics was given by @jeffhecht in @OPNmagazine

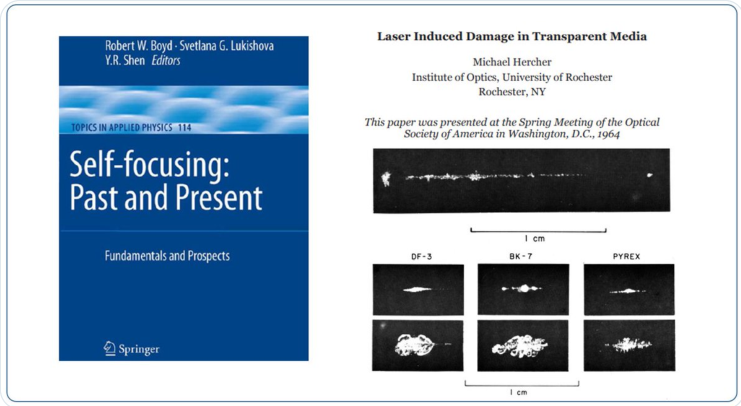
How the Laser Launched Nonlinear Optics

If the laser was a solution, nonlinear optics was one of the problems it was seeking. Intense pulses of coherent, monochromatic light were just what was needed to produce nonlinear effects. Once phys…

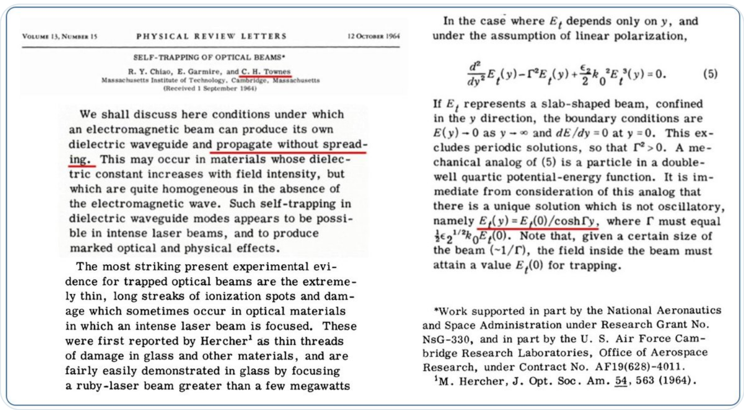
https://www.osapublishing.org/opn/abstract.cfm?uri=opn-21-11-34

The article includes the photo of the first "self-trapping" experiment that kicked off the study of spatial solitons.

But Hercher’s photos of these laser damage tracks were not actually published at the time! His abstract in JOSAB Vol. 54, 563, 1964 was text only. The images only appeared in print 45 years later in the 2009 edited volume by @BoydNLOLab & Profs Lukishova & Shen.



Chiao, Garmire and Townes published the theory of spatial solitons in October 1964, which included what many believe to be the first statement of the cubic NLSE in optics and the sech-soliton solution. This paper had only one reference (to Hercher)!


VOLUME 13, NUMBER 15 PHYSICAL REVIEW LETTERS 12 OCTOBER 1964

SELF-TRAPPING OF OPTICAL BEAMS*

R. Y. Chiao, E. Garmire, and C. H. Townes
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 1 September 1964)

We shall discuss here conditions under which an electromagnetic beam can produce its own dielectric waveguide and propagate without spreading. This may occur in materials whose dielectric constant increases with field intensity, but which are quite homogeneous in the absence of the electromagnetic wave. Such self-trapping in dielectric waveguide modes appears to be possible in intense laser beams, and to produce marked optical and physical effects.

The most striking present experimental evidence for trapped optical beams are the extremely thin, long streaks of ionization spots and damage which sometimes occur in optical materials in which an intense laser beam is focused. These were first reported by Hercher[1] as thin threads of damage in glass and other materials, and are fairly easily demonstrated in glass by focusing a ruby-laser beam greater than a few megawatts

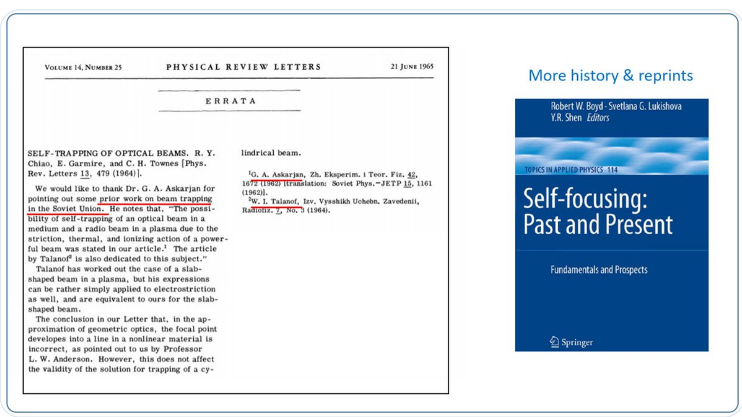
In the case where E_t depends only on y, and under the assumption of linear polarization,

$$\frac{d^2}{dy^2}E_t(y)-\Gamma^2 E_t(y)+\frac{\epsilon_2}{2}k_0^2 E_t^3(y)=0. \qquad (5)$$

If E_t represents a slab-shaped beam, confined in the y direction, the boundary conditions are $E(y)\to 0$ as $y\to\infty$ and $dE/dy=0$ at $y=0$. This excludes periodic solutions, so that $\Gamma^2>0$. A mechanical analog of (5) is a particle in a double-well quartic potential-energy function. It is immediate from consideration of this analog that there is a unique solution which is not oscillatory, namely $E_t(y)=E_t(0)/\cosh\Gamma y$, where Γ must equal $\frac{1}{2}\epsilon_2^{1/2}k_0E_t(0)$. Note that, given a certain size of the beam ($\sim 1/\Gamma$), the field inside the beam must attain a value $E_t(0)$ for trapping.

*Work supported in part by the National Aeronautics and Space Administration under Research Grant No. NsG-330, and in part by the U. S. Air Force Cambridge Research Laboratories, Office of Aerospace Research, under Contract No. AF19(628)-4011.
[1]M. Hercher, J. Opt. Soc. Am. 54, 563 (1964).

But was it the first? In June 1965 Townes published a correction, acknowledging earlier work by Askarjan and Talanov. Reprints of these hard to find early papers are in the edited volume by @BoydNLOLab & Profs Lukishova & Shen.



VOLUME 14, NUMBER 25 PHYSICAL REVIEW LETTERS 21 JUNE 1965

ERRATA

SELF-TRAPPING OF OPTICAL BEAMS. R. Y. Chiao, E. Garmire, and C. H. Townes [Phys. Rev. Letters 13, 479 (1964)].

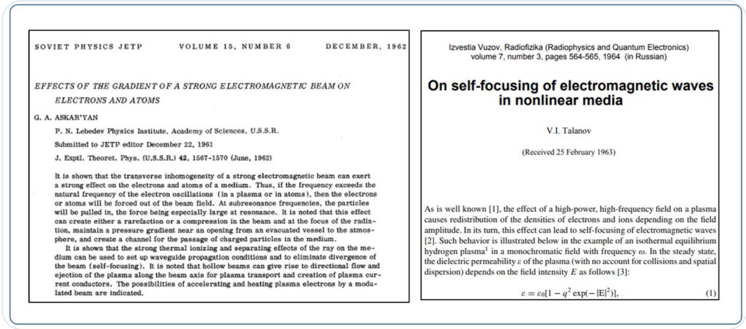
We would like to thank Dr. G. A. Askarjan for pointing out some prior work on beam trapping in the Soviet Union. He notes that, "The possibility of self-trapping of an optical beam in a medium and a radio beam in a plasma due to the striction, thermal, and ionizing action of a powerful beam was stated in our article.[1] The article by Talanof[2] is also dedicated to this subject."

Talanof has worked out the case of a slab-shaped beam in a plasma, but his expressions can be rather simply applied to electrostriction as well, and are equivalent to ours for the slab-shaped beam.

The conclusion in our Letter that, in the approximation of geometric optics, the focal point developes into a line in a nonlinear material is incorrect, as pointed out to us by Professor L. W. Anderson. However, this does not affect the validity of the solution for trapping of a cylindrical beam.

[1]G. A. Askarjan, Zh. Eksperim. i Teor. Fiz. 42, 1672 (1962) [translation: Soviet Phys.—JETP 15, 1161 (1962)].
[2]W. I. Talanof, Izv. Vysshikh Uchebn. Zavedenii, Radiofiz. 7, No. 3 (1964).

Here are those two early papers!



SOVIET PHYSICS JETP VOLUME 15, NUMBER 6 DECEMBER, 1962

EFFECTS OF THE GRADIENT OF A STRONG ELECTROMAGNETIC BEAM ON ELECTRONS AND ATOMS

G. A. ASKAR'YAN

P. N. Lebedev Physics Institute, Academy of Sciences, U.S.S.R.

Submitted to JETP editor December 22, 1961

J. Exptl. Theoret. Phys. (U.S.S.R.) **42**, 1567-1570 (June, 1962)

It is shown that the transverse inhomogeneity of a strong electromagnetic beam can exert a strong effect on the electrons and atoms of a medium. Thus, if the frequency exceeds the natural frequency of the electron oscillations (in a plasma or in atoms), then the electrons or atoms will be forced out of the beam field. At subresonance frequencies, the particles will be pulled in, the force being especially large at resonance. It is noted that this effect can create either a rarefaction or a compression in the beam and at the focus of the radiation, maintain a pressure gradient near an opening from an evacuated vessel to the atmosphere, and create a channel for the passage of charged particles in the medium.

It is shown that the strong thermal ionizing and separating effects of the ray on the medium can be used to set up waveguide propagation conditions and to eliminate divergence of the beam (self-focusing). It is noted that hollow beams can give rise to directional flow and ejection of the plasma along the beam axis for plasma transport and creation of plasma current conductors. The possibilities of accelerating and heating plasma electrons by a modulated beam are indicated.

Izvestia Vuzov, Radiofizika (Radiophysics and Quantum Electronics) volume 7, number 3, pages 564-565, 1964 (in Russian)

On self-focusing of electromagnetic waves in nonlinear media

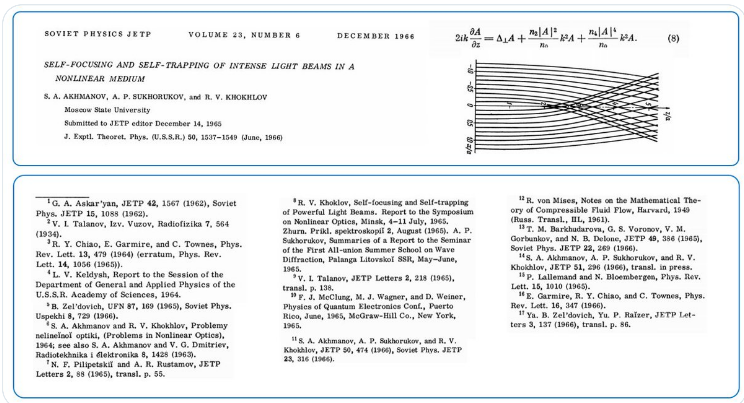
V.I. Talanov

(Received 25 February 1963)

As is well known [1], the effect of a high-power, high-frequency field on a plasma causes redistribution of the densities of electrons and ions depending on the field amplitude. In its turn, this effect can lead to self-focusing of electromagnetic waves [2]. Such behavior is illustrated below in the example of an isothermal equilibrium hydrogen plasma[1] in a monochromatic field with frequency ω. In the steady state, the dielectric permeability ε of the plasma (with no account for collisions and spatial dispersion) depends on the field intensity E as follows [3]:

$$\varepsilon = \varepsilon_0[1 - q^2 \exp(-|E|^2)], \qquad (1)$$

In December 1966, Akhmanov, Sukhorukov and Khokhlov published further independent theoretical studies studying the cubic NLSE, showing the extensive work carried out in the USSR.



SOVIET PHYSICS JETP VOLUME 23, NUMBER 6 DECEMBER 1966

SELF-FOCUSING AND SELF-TRAPPING OF INTENSE LIGHT BEAMS IN A NONLINEAR MEDIUM

S. A. AKHMANOV, A. P. SUKHORUKOV, and R. V. KHOKHLOV

Moscow State University

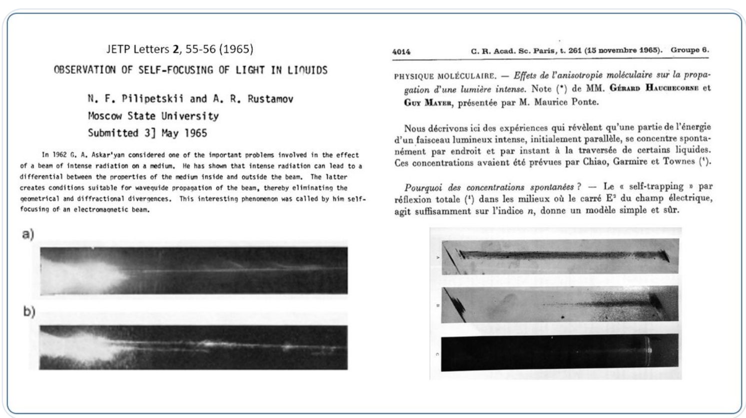
Submitted to JETP editor December 14, 1965

J. Exptl. Theoret. Phys. (U.S.S.R.) **50**, 1537–1549 (June, 1966)

$$2ik\frac{\partial A}{\partial z} = \Delta_\perp A + \frac{n_2|A|^2}{n_0}k^2A + \frac{n_4|A|^4}{n_0}k^2A. \qquad (8)$$

[1] G. A. Askar'yan, JETP **42**, 1567 (1962), Soviet Phys. JETP **15**, 1088 (1962).
[2] V. I. Talanov, Izv. Vuzov, Radiofizika **7**, 564 (1934).
[3] R. Y. Chiao, E. Garmire, and C. Townes, Phys. Rev. Lett. **13**, 479 (1964) (erratum, Phys. Rev. Lett. **14**, 1056 (1965)).
[4] L. V. Keldysh, Report to the Session of the Department of General and Applied Physics of the U.S.S.R. Academy of Sciences, 1964.
[5] B. Zel'dovich, UFN **87**, 169 (1965), Soviet Phys. Uspekhi **8**, 729 (1966).
[6] S. A. Akhmanov and R. V. Khokhlov, Problemy nelineĭnoĭ optiki, (Problems in Nonlinear Optics), 1964; see also S. A. Akhmanov and V. G. Dmitriev, Radiotekhnika i élektronika **8**, 1428 (1963).
[7] N. F. Pilipetskiĭ and A. R. Rustamov, JETP Letters **2**, 88 (1965), transl. p. 55.
[8] R. V. Khoklov, Self-focusing and Self-trapping of Powerful Light Beams. Report to the Symposium on Nonlinear Optics, Minsk, 4–11 July, 1965. Zhurn. Prikl. spektroskopiĭ **2**, August (1965). A. P. Sukhorukov, Summaries of a Report to the Seminar of the First All-union Summer School on Wave Diffraction, Palanga Litovskoĭ SSR, May–June, 1965.
[9] V. I. Talanov, JETP Letters **2**, 218 (1965), transl. p. 138.
[10] F. J. McClung, M. J. Wagner, and D. Weiner, Physics of Quantum Electronics Conf., Puerto Rico, June, 1965, McGraw-Hill Co., New York, 1965.
[11] S. A. Akhmanov, A. P. Sukhorukov, and R. V. Khokhlov, JETP **50**, 474 (1966), Soviet Phys. JETP **23**, 316 (1966).
[12] R. von Mises, Notes on the Mathematical Theory of Compressible Fluid Flow, Harvard, 1949 (Russ. Transl., IIL, 1961).
[13] T. M. Barkhudarova, G. S. Voronov, V. M. Gorbunkov, and N. B. Delone, JETP **49**, 386 (1965), Soviet Phys. JETP **22**, 269 (1966).
[14] S. A. Akhmanov, A. P. Sukhorukov, and R. V. Khokhlov, JETP **51**, 296 (1966), transl. in press.
[15] P. Lallemand and N. Bloembergen, Phys. Rev. Lett. **15**, 1010 (1965).
[16] E. Garmire, R. Y. Chiao, and C. Townes, Phys. Rev. Lett. **16**, 347 (1966).
[17] Ya. B. Zel'dovich, Yu. P. Raĭzer, JETP Letters **3**, 137 (1966), transl. p. 86.

Experimental interest was evident and confirmation took place around the world. Self-focusing in liquids was reported by Pilipetskii & Rustamov (published 25 July 1965) and Hauchecorne & Mayer in France (published 15 November 1965).



JETP Letters **2**, 55-56 (1965)

OBSERVATION OF SELF-FOCUSING OF LIGHT IN LIQUIDS

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.

a)

b)

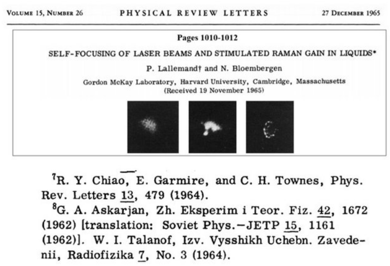
4014 C. R. Acad. Sc. Paris, t. 261 (15 novembre 1965). Groupe 6.

PHYSIQUE MOLÉCULAIRE. — *Effets de l'anisotropie moléculaire sur la propagation d'une lumière intense.* Note (*) de MM. **Gérard Hauchecorne** et **Guy Mayer**, présentée par M. Maurice Ponte.

Nous décrivons ici des expériences qui révèlent qu'une partie de l'énergie d'un faisceau lumineux intense, initialement parallèle, se concentre spontanément par endroit et par instant à la traversée de certains liquides. Ces concentrations avaient été prévues par Chiao, Garmire et Townes (1).

Pourquoi des concentrations spontanées ? — Le « self-trapping » par réflexion totale (1) dans les milieux où le carré E^2 du champ électrique, agit suffisamment sur l'indice n, donne un modèle simple et sûr.

In the USA, the most well-known experiment was that from Bloembergen's group, published in December 1965. Bloembergen cited Askarjan and Talanov, but he was unaware of the earlier independent experiments in the Soviet Union and France. No email in those days remember!


VOLUME 15, NUMBER 26 PHYSICAL REVIEW LETTERS 27 DECEMBER 1965

Pages 1010-1012

SELF-FOCUSING OF LASER BEAMS AND STIMULATED RAMAN GAIN IN LIQUIDS*

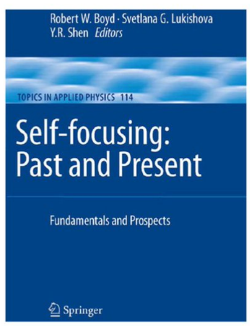
P. Lallemand† and N. Bloembergen

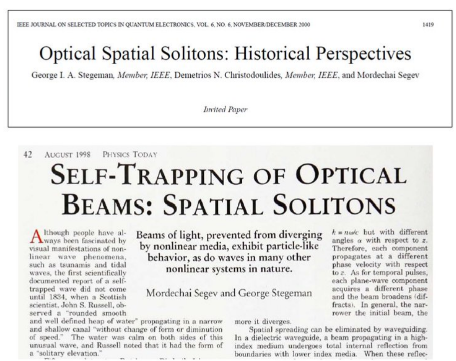
Gordon McKay Laboratory, Harvard University, Cambridge, Massachusetts
(Received 19 November 1965)

[7] R. Y. Chiao, E. Garmire, and C. H. Townes, Phys. Rev. Letters 13, 479 (1964).
[8] G. A. Askarjan, Zh. Eksperim i Teor. Fiz. 42, 1672 (1962) [translation: Soviet Phys.—JETP 15, 1161 (1962)]. W. I. Talanof, Izv. Vysshikh Uchebn. Zavedenii, Radiofizika 7, No. 3 (1964).

Harvard University, courtesy AIP Emilio Segre Visual Archives

However we need to clarify some physics. Ideal NLSE spatial solitons are seen only under specific conditions & Hercher's damage tracks were actually caused by more complex filamentation. But they still motivated the development of a whole new field!




IEEE JOURNAL ON SELECTED TOPICS IN QUANTUM ELECTRONICS, VOL. 6, NO. 6, NOVEMBER/DECEMBER 2000 1419

Optical Spatial Solitons: Historical Perspectives

George I. A. Stegeman, *Member, IEEE*, Demetrios N. Christodoulides, *Member, IEEE*, and Mordechai Segev

Invited Paper

42 AUGUST 1998 PHYSICS TODAY

SELF-TRAPPING OF OPTICAL BEAMS: SPATIAL SOLITONS

Beams of light, prevented from diverging by nonlinear media, exhibit particle-like behavior, as do waves in many other nonlinear systems in nature.

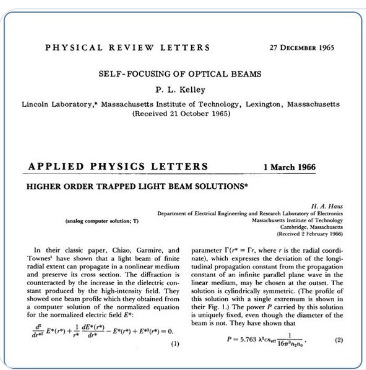
Mordechai Segev and George Stegeman

Although people have always been fascinated by visual manifestations of nonlinear wave phenomena, such as tsunamis and tidal waves, the first scientifically documented report of a self-trapped wave did not come until 1834, when a Scottish scientist, John S. Russell, observed a "rounded smooth and well defined heap of water" propagating in a narrow and shallow canal "without change of form or diminution of speed." The water was calm on both sides of this unusual wave, and Russell noted that it had the form of a "solitary elevation."

$k = n\omega/c$ but with different angles α with respect to z. Therefore, each component propagates at a different phase velocity with respect to z. As for temporal pulses, each plane-wave component acquires a different phase and the beam broadens (diffracts). In general, the narrower the initial beam, the more it diverges.

Spatial spreading can be eliminated by waveguiding. In a dielectric waveguide, a beam propagating in a high-index medium undergoes total internal reflection from boundaries with lower index media. When these reflec-

Major contributions to self-focusing and self-trapping were made by Kelley & Haus. An important point is that understanding filamentation requires a spatio-temporal dynamical model. This was first suggested by Lugovoi & Prokhorov and Marburger & Dawes.


PHYSICAL REVIEW LETTERS 27 DECEMBER 1965

SELF-FOCUSING OF OPTICAL BEAMS

P. L. Kelley

Lincoln Laboratory,* Massachusetts Institute of Technology, Lexington, Massachusetts
(Received 21 October 1965)

APPLIED PHYSICS LETTERS 1 March 1966

HIGHER ORDER TRAPPED LIGHT BEAM SOLUTIONS*

(analog computer solution; T)

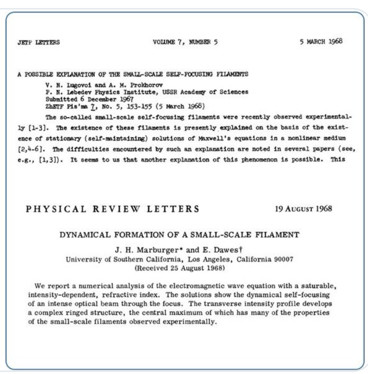
H. A. Haus
Department of Electrical Engineering and Research Laboratory of Electronics
Massachusetts Institute of Technology
Cambridge, Massachusetts
(Received 2 February 1966)

In their classic paper, Chiao, Garmire, and Townes[1] have shown that a light beam of finite radial extent can propagate in a nonlinear medium and preserve its cross section. The diffraction is counteracted by the increase in the dielectric constant produced by the high-intensity field. They showed one beam profile which they obtained from a computer solution of the normalized equation for the normalized electric field E^*:

$$\frac{d^2}{dr^{*2}}E^*(r^*) + \frac{1}{r^*}\frac{dE^*(r^*)}{dr^*} - E^*(r^*) + E^{*3}(r^*) = 0. \quad (1)$$

parameter $\Gamma(r^* = \Gamma r$, where r is the radial coordinate), which expresses the deviation of the longitudinal propagation constant from the propagation constant of an infinite parallel plane wave in the linear medium, may be chosen at the outset. The solution is cylindrically symmetric. (The profile of this solution with a single extremum is shown in their Fig. 1.) The power P carried by this solution is uniquely fixed, even though the diameter of the beam is not. They have shown that

$$P = 5.763\ \lambda^2 c n_{eff} \frac{1}{16\pi^3 n_2 n_0}, \quad (2)$$


JETP LETTERS VOLUME 7, NUMBER 5 5 MARCH 1968

A POSSIBLE EXPLANATION OF THE SMALL-SCALE SELF-FOCUSING FILAMENTS

V. N. Lugovoi and A. M. Prokhorov
P. N. Lebedev Physics Institute, USSR Academy of Sciences
Submitted 6 December 1967
ZhETF Pis'ma 7, No. 5, 153-155 (5 March 1968)

The so-called small-scale self-focusing filaments were recently observed experimentally [1-3]. The existence of these filaments is presently explained on the basis of the existence of stationary (self-maintaining) solutions of Maxwell's equations in a nonlinear medium [2,4-6]. The difficulties encountered by such an explanation are noted in several papers (see, e.g., [1,3]). It seems to us that another explanation of this phenomenon is possible. This

PHYSICAL REVIEW LETTERS 19 AUGUST 1968

DYNAMICAL FORMATION OF A SMALL-SCALE FILAMENT

J. H. Marburger* and E. Dawes†
University of Southern California, Los Angeles, California 90007
(Received 25 August 1968)

We report a numerical analysis of the electromagnetic wave equation with a saturable, intensity-dependent, refractive index. The solutions show the dynamical self-focusing of an intense optical beam through the focus. The transverse intensity profile develops a complex ringed structure, the central maximum of which has many of the properties of the small-scale filaments observed experimentally.

Haus's paper may be one of those early papers (like the more celebrated FPU case) where a woman "computer" did the programming, but this wasn't considered deserving of being recognized as a co-author.

APPLIED PHYSICS LETTERS 1 March 1966

HIGHER ORDER TRAPPED LIGHT BEAM SOLUTIONS*

H. A. Haus
Department of Electrical Engineering and Research Laboratory of Electronics
Massachusetts Institute of Technology
Cambridge, Massachusetts
(Received 2 February 1966)

(analog computer solution; T)

In their classic paper, Chiao, Garmire, and Townes[1] have shown that a light beam of finite radial extent can propagate in a nonlinear medium and preserve its cross section. The diffraction is counteracted by the increase in the dielectric constant produced by the high-intensity field. They showed one beam profile which they obtained from a computer solution of the normalized equation for the normalized electric field E^*:

$$\frac{d^2}{dr^{*2}}E^*(r^*) + \frac{1}{r^*}\frac{dE^*(r^*)}{dr^*} - E^*(r^*) + E^{*3}(r^*) = 0. \quad (1)$$

parameter $\Gamma(r^* = \Gamma r$, where r is the radial coordinate), which expresses the deviation of the longitudinal propagation constant from the propagation constant of an infinite parallel plane wave in the linear medium, may be chosen at the outset. The solution is cylindrically symmetric. (The profile of this solution with a single extremum is shown in their Fig. 1.) The power P carried by this solution is uniquely fixed, even though the diameter of the beam is not. They have shown that

$$P = 5.763\,\lambda^2 c n_{eff}\frac{1}{16\pi^3 n_2 n_0}, \quad (2)$$

The author gratefully acknowledges discussions with Dr. P. L. Kelley, the help of Miss Martha M. Pennell, who carried out the computations, and the use of the Project MAC Computer facility.

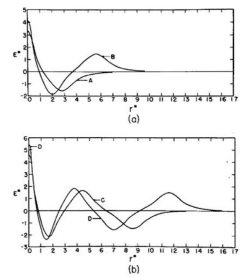


Fig. 1. Computer solutions: (a) 1 and 2 rings; (b) 3 and 4 rings.

Back in the USSR, Akhmanov, Sukhorukov and Khokhlov published a long review paper in 1967 and established the Russian school of nonlinear and coherent optics.

SOVIET PHYSICS
USPEKHI
A Translation of Uspekhi Fizicheskikh Nauk
É. V. Shpol'skiĭ (Editor in Chief), S. G. Suvorov (Associate Editor), D. I. Blokhintsev, V. L. Ginzburg, B. B. Kadomtsev, L. D. Keldysh, S. T. Konobeevskiĭ, F. L. Shapiro, V. A. Ugarov, V. I. Veksler, Ya. B. Zel'dovich (Editorial Board).

SOVIET PHYSICS USPEKHI (Russian Vol. 93, Nos. 1 and 2) MARCH-APRIL 1968

SELF-FOCUSING AND DIFFRACTION OF LIGHT IN A NONLINEAR MEDIUM

S. A. AKHMANOV, A. P. SUKHORUKOV, and R. V. KHOKHLOV
Moscow State University
Usp. Fiz. Nauk 93, 19–70 (September, 1967)

CONTENTS

1. INTRODUCTION

1.1. Effects of Self Interaction of Electromagnetic Waves in a Nonlinear Medium. Experimental Data

AMONG the nonlinear optical effects that have been intensely investigated in recent years, a special position is occupied by effects of self-action of powerful light waves. Self-action effects are connected with the dependence of the complex dielectric constant (complex refractive index) on the intensity of the propagating wave. The appearance of this dependence can be connected with various physical causes. Electrostriction in a light field leads to the appearance of a pressure $p = E^2/8\pi \cdot \rho\partial\epsilon/\partial\rho$ (E—intensity of light field, ρ—density, ε—dielectric constant), which changes the density in the region occupied by the light beam, and consequently also the refractive index of the medium. In a liquid, a strong light field leads to orientation of the anisotropically polarized molecules, owing to the interaction with the induced dipole moment; the medium then becomes anisotropic and the average refractive index for the orienting field increases. This effect is customarily called the high-frequency Kerr effect; as in the well known static Kerr effect, the variation of the refractive index is produced in this case, as a result of the "alignment" of the molecules in the field. The refractive-index increment, which depends on the intensity of the light wave, can also be connected with the nonlinearity of the electron polarization. Finally, the change of the density, and consequently also of the refractive index, can be connected with heating due to dissipation of energy by the powerful light wave. A more detailed discussions of these effects will be deferred to Sec. 1.2, and we shall turn now to an examination of the singularities of the wave phenomena in media with a refractive index that depends on the intensity of the light wave. It is possible to explain many features of the wave processes without resorting to a detailed consideration of the physical mechanism of the nonlinearity, confining oneself to a phenomenological description of the polarization of the medium. The phenomenonlogical effects of the self-action are described by the odd terms (with respect to the field E) in the expansion of the nonlinear part of the polarization of the nonlinear medium with respect to the field, that is, if we represent the i-th component of the vector of the nonlinear polarization $P^{(nl)}$ in the form

609

Vladimir A Makarov 2004 *Phys.-Usp.* **47** 1059

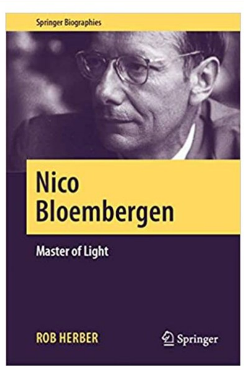
Quantum electronics and the R V Khokhlov–S A Akhmanov school of coherent and nonlinear optics at Moscow State University

V A Makarov

The formation of the R V Khokhlov–S A Akhmanov scientific school of coherent and nonlinear optics is inseparably linked with the onset and progress of quantum electronic research in Russia. Moreover, it has been universally recognized that R V Khokhlov and S A Akhmanov are among the few founders of contemporary nonlinear optics.

Figure 1. S A Akhmanov and R V Khokhlov in the early 1960s.

Ahkmanov, Khokhlov and Bloembergen became friends, with mutual visits between the USA and Russia.



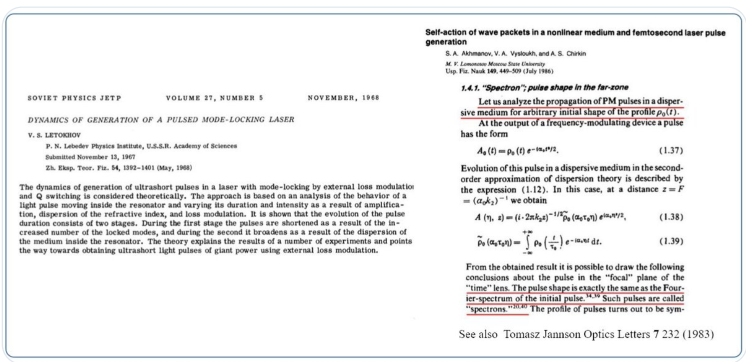
From Nico Bloembergen, Master of Light. Springer (2009)

In 1967 he also visited the Moscow State University and was received there by Rem V. Khokhlov and Sergei A. Akhmanov who had just received the Lenin Prize for their research. In the hall of the university there was a large mural, where Khohklov and Akhmanow were depicted as young horsemen who triumphantly overcame the fields of non-linear optics. Their research was in the same field as the work done by Bloembergen's group. Khohklov and Bloembergen had met at conferences and privately on many occasions. Bloembergen had invited Khokhlov to his home in Lexington after they had both attended a Gordon Research Conference in New Hampshire. In 1971 Bloembergen and Deli were guests in the Moscow apartment of Khokhlov and his wife Lena. Khokhlov was appointed rector of the Moscow State University, the highest educational position in the Soviet Union. Bloembergen also had a good relationship with Akhmanov. Akhmanov and his wife invited the Bloembergens to their dacha outside Moscow in 1971. Akhmanov also came to the Bloembergens' house after participating in a Gordon Research Conference.

In 1975, the E. Fermi Course 64 on Nonlinear Spectroscopy was held in Varenna, Italy. Bloembergen was course leader and editor of the course reports, the *Proceedings*. Akhmanov was one of the most important lecturers and brought vodka and caviar from Moscow for the evening party. Bloembergen states that these encounters were not only enjoyable, but also an intense intellectual challenge. After the course, Bloembergen was exhausted, so much so that he lacked the inspiration to give the closing speech. Deli made a number of good suggestions, but none really inspired

In 1967, Khokhlov & Akhmanov received the Lenin Prize, celebrated with a mural of them on a horse upon an SHG crystal. This photo was provided by Profs Makharov & Lukishova to @jeffhecht for his 2010 article.

Much early Russian work foreshadowed current areas of research that we are exploiting on a daily basis e.g. mode-locking dynamics and the real-time dispersive Fourier transform ("spectron")



SOVIET PHYSICS JETP VOLUME 27, NUMBER 5 NOVEMBER, 1968

DYNAMICS OF GENERATION OF A PULSED MODE-LOCKING LASER

V. S. LETOKHOV

P. N. Lebedev Physics Institute, U.S.S.R. Academy of Sciences

Submitted November 13, 1967

Zh. Eksp. Teor. Fiz. 54, 1392–1401 (May, 1968)

The dynamics of generation of ultrashort pulses in a laser with mode-locking by external loss modulation and Q switching is considered theoretically. The approach is based on an analysis of the behavior of a light pulse moving inside the resonator and varying its duration and intensity as a result of amplification, dispersion of the refractive index, and loss modulation. It is shown that the evolution of the pulse duration consists of two stages. During the first stage the pulses are shortened as a result of the increased number of the locked modes, and during the second it broadens as a result of the dispersion of the medium inside the resonator. The theory explains the results of a number of experiments and points the way towards obtaining ultrashort light pulses of giant power using external loss modulation.

Self-action of wave packets in a nonlinear medium and femtosecond laser pulse generation

S. A. Akhmanov, V. A. Vysloukh, and A. S. Chirkin

M. V. Lomonosov Moscow State University

Usp. Fiz. Nauk 149, 449–509 (July 1986)

1.4.1. "Spectron"; pulse shape in the far-zone

Let us analyze the propagation of PM pulses in a dispersive medium for arbitrary initial shape of the profile $\rho_0(t)$.

At the output of a frequency-modulating device a pulse has the form

$$A_0(t) = \rho_0(t)\, e^{-i\alpha_0 t^2/2}. \qquad (1.37)$$

Evolution of this pulse in a dispersive medium in the second-order approximation of dispersion theory is described by the expression (1.12). In this case, at a distance $z = F = (\alpha_0 k_2)^{-1}$ we obtain

$$A(\eta, z) = (i \cdot 2\pi k_2 z)^{-1/2} \tilde{\rho}_0(\alpha_0 \tau_0 \eta)\, e^{i\alpha_0 \eta^2/2}, \qquad (1.38)$$

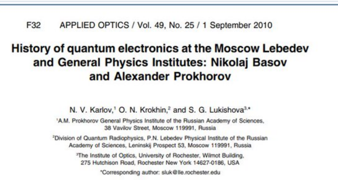
$$\tilde{\rho}_0(\alpha_0 \tau_0 \eta) = \int_{-\infty}^{+\infty} \rho_0\left(\frac{t}{\tau_0}\right) e^{-i\alpha_0 \eta t}\, dt. \qquad (1.39)$$

From the obtained result it is possible to draw the following conclusions about the pulse in the "focal" plane of the "time" lens. The pulse shape is exactly the same as the Fourier-spectrum of the initial pulse.[34,39] Such pulses are called "spectrons."[20,40] The profile of pulses turns out to be sym-

See also Tomasz Jannson Optics Letters 7 232 (1983)

A memorial plaque to S.A. Akhmanov is now in the hall of the Nonlinear Optics Building of Moscow State University, made by the sculptor L.E. Kerbel and installed in 1994.

To learn even more about the many Russian contributions to the early maser and laser era (especially the neglected work of Valentin Fabrikant), two great historical review papers are here!



F32 APPLIED OPTICS / Vol. 49, No. 25 / 1 September 2010

History of quantum electronics at the Moscow Lebedev and General Physics Institutes: Nikolaj Basov and Alexander Prokhorov

N. V. Karlov,[1] O. N. Krokhin,[2] and S. G. Lukishova[3,*]

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[3]The Institute of Optics, University of Rochester, Wilmot Building, 275 Hutchison Road, Rochester New York 14627-0186, USA

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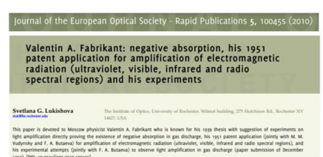


Journal of the European Optical Society - Rapid Publications 5, 10045s (2010)

Valentin A. Fabrikant: negative absorption, his 1951 patent application for amplification of electromagnetic radiation (ultraviolet, visible, infrared and radio spectral regions) and his experiments

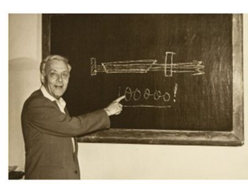
Svetlana G. Lukishova sluk@lle.rochester.edu

The Institute of Optics, University of Rochester, Wilmot building, 275 Hutchison Rd., Rochester NY 14627, USA

This paper is devoted to Moscow physicist Valentin A. Fabrikant who is known for his 1939 thesis with suggestion of experiments on light amplification directly proving the existence of negative absorption in gas discharge, his 1951 patent application (jointly with M. M. Vudynsky and F. A. Butaeva) for amplification of electromagnetic radiation (ultraviolet, visible, infrared and radio spectral regions), and his experimental attempts (jointly with F. A. Butaeva) to observe light amplification in gas discharge (paper submission of December 1957). [DOI: 10.2971/jeos.2010.10045s]

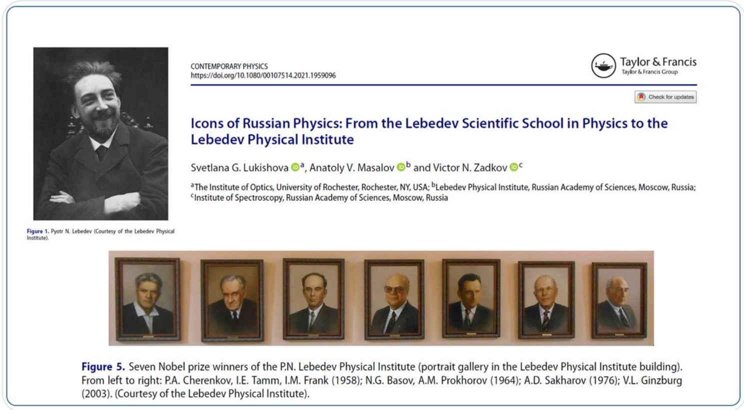
Prokhorov & Basov

Fabrikant & Vavilov



Fabrikant lecturing

Another review focusing on the Lebedev institute is here!



CONTEMPORARY PHYSICS
https://doi.org/10.1080/00107514.2021.1959096

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Icons of Russian Physics: From the Lebedev Scientific School in Physics to the Lebedev Physical Institute

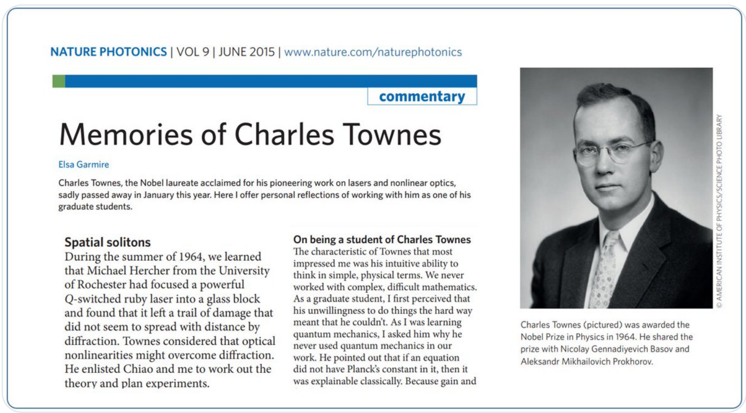
Svetlana G. Lukishova [a], Anatoly V. Masalov [b] and Victor N. Zadkov [c]

[a]The Institute of Optics, University of Rochester, Rochester, NY, USA; [b]Lebedev Physical Institute, Russian Academy of Sciences, Moscow, Russia; [c]Institute of Spectroscopy, Russian Academy of Sciences, Moscow, Russia

Figure 1. Pyotr N. Lebedev (Courtesy of the Lebedev Physical Institute).

Figure 5. Seven Nobel prize winners of the P.N. Lebedev Physical Institute (portrait gallery in the Lebedev Physical Institute building). From left to right: P.A. Cherenkov, I.E. Tamm, I.M. Frank (1958); N.G. Basov, A.M. Prokhorov (1964); A.D. Sakharov (1976); V.L. Ginzburg (2003). (Courtesy of the Lebedev Physical Institute).

And some wonderful memories from Elsa Garmire of the early work with Charles Townes were published in 2015 in @NaturePhotonics



NATURE PHOTONICS | VOL 9 | JUNE 2015 | www.nature.com/naturephotonics

commentary

Memories of Charles Townes

Elsa Garmire

Charles Townes, the Nobel laureate acclaimed for his pioneering work on lasers and nonlinear optics, sadly passed away in January this year. Here I offer personal reflections of working with him as one of his graduate students.

Spatial solitons
During the summer of 1964, we learned that Michael Hercher from the University of Rochester had focused a powerful *Q*-switched ruby laser into a glass block and found that it left a trail of damage that did not seem to spread with distance by diffraction. Towнes considered that optical nonlinearities might overcome diffraction. He enlisted Chiao and me to work out the theory and plan experiments.

On being a student of Charles Townes
The characteristic of Townes that most impressed me was his intuitive ability to think in simple, physical terms. We never worked with complex, difficult mathematics. As a graduate student, I first perceived that his unwillingness to do things the hard way meant that he couldn't. As I was learning quantum mechanics, I asked him why he never used quantum mechanics in our work. He pointed out that if an equation did not have Planck's constant in it, then it was explainable classically. Because gain and

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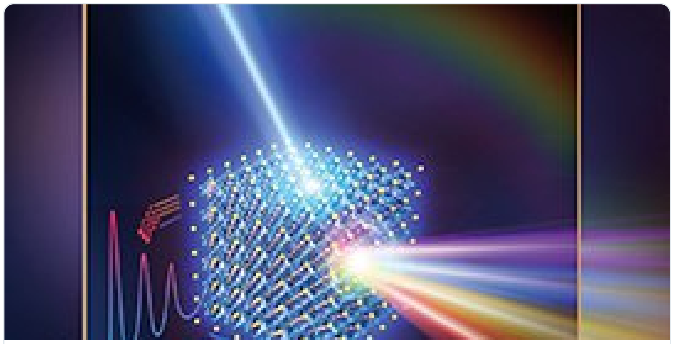
Charles Townes (pictured) was awarded the Nobel Prize in Physics in 1964. He shared the prize with Nicolay Gennadiyevich Basov and Aleksandr Mikhailovich Prokhorov.

Conclusions. The early days of laser and nonlinear optics were extremely international, & historical articles are important. Use these examples in teaching, and download @SPIEtweets Nobel prize poster for your lab!



Light, Lasers, and the Nobel Prize

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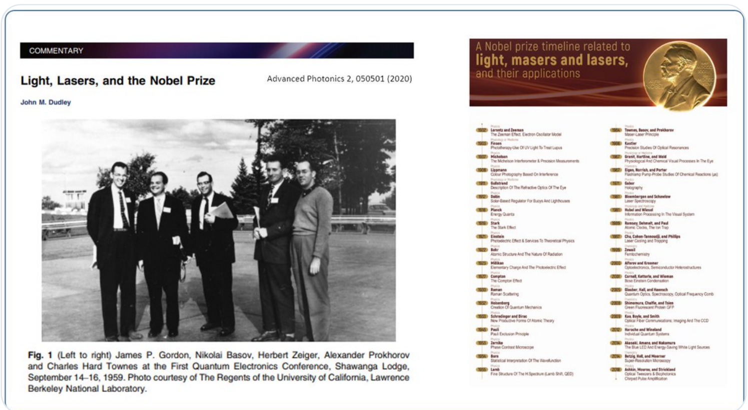

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