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Optics in Estonia: Research and Innovation Highlights †

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Abstract: Based on citation data, an overview of that part of Estonian basic physical research where optical phenomena or optical methods themselves are the subjects of study is given. The second part of the overview introduces the design and production of optical instruments in Estonia.

Keywords: optics; Web of Science; Google Scholar; Estonia

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1. Introduction

In today's world, where there is practically an infinite amount of information, all claiming people's time and interest, something has an advantage in attracting attention if it is associated with a brand, a widely known name, a story, or a legend that stimulates the imagination. That is why one could ask if there has been anybody among Estonians (whose total population is only 1.3 million) who has left a legendary mark on the history of optics in the world. Yes, we can proudly shout: we did have such a man, telescope to the sky, and roots in the water around the island Naissaar to the north from Tallinn—the capital of the Republic of Estonia. This man was Bernhard Schmidt, who came up with a brilliant idea to improve the telescope's image with a corrective optical element (now called the "Schmidt corrector plate"). While working in Germany in the 1930s, he derived the exact equation of the surface of the element and realized it in glass. The task required fanatical, laborious, and grinding work with utmost precision. He could use only one hand because he lost the other one in an accident on Naissaar while experimenting with one of his other inventions. Thanks to the correction for the optical errors of spherical aberration, coma, and astigmatism, the Schmidt camera or the Schmidt telescope gives unprecedentedly sharp and clear star images and caused a revolution in optical astronomy, in recognition of which a minor planet (asteroid) was given his name. For decades, the Schmidt system telescopes have been set up in several observatories, including "Big Schmidt" at Mount Palomar in California and the world's largest one at the Schwarzchild Observatory in Germany.

But academic optical research in Estonia did not emerge until the 1950s, when luminescence studies began in Tartu. The mainstream of this research was, and still is, the application of luminescence spectroscopy to studies in condensed matter physics and materials science, to which most of the publications of Estonian physicists have been devoted. For example, in the first decade of the century, a couple of Estonian material scientists reached 1% of the most cited researchers in their field according to the Essential Science Indicators issued by the Clarivate Web of Science.

In this short overview, we restrict ourselves to such basic research where optical phenomena or the methods themselves are the subjects of study, not applications of them for studying other subjects—gases, solids, molecules, biological systems, etc. The second part of the overview is devoted to the design and production of optical instruments in Estonia.

2. Highlights of Basic Research

The research highlights have been singled out according to the following criteria: (i) work has been carried out in Estonia, and (ii) resulting pioneering publications are widely recognized, i.e., have been cited hundreds (and no less than half a hundred) times according to the Web of Science and/or Google Scholar. For each highlight listed below, up to four such references are given in chronological order. If an internationally acknowledged publisher has issued a monograph devoted to the emerging research field, the corresponding reference is also given.

2.1. Development of Photoelasticity Methods for Stress Measurement in Glass

The photoelastic effect (also called the piezo-optical effect) is the change in the refractive index and the emergence of birefringence caused by stress. Photoelasticity as an experimental technique enables non-invasive measurement of external or residual stress distributions in glass and other transparent materials [1–5]. Reference [5] has been cited 362/161 times (here and henceforth the Google Scholar's number of citations is given before the slash and the Web of Science's number after the slash, data from February 2023). The most beautiful and prominent application of the technique was solving a four-century-old mystery of the extraordinary strength of Prince Rupert's drops (see Figure 1, also known as Dutch or Batavian glass tears) in 2016. Since the key role in reaching the solution belonged to the company Glasstress, a spin-off of the Tallinn University of Technology, which was founded by the author of [1], we shall return to the applications of photoelasticity in the second part of our overview.

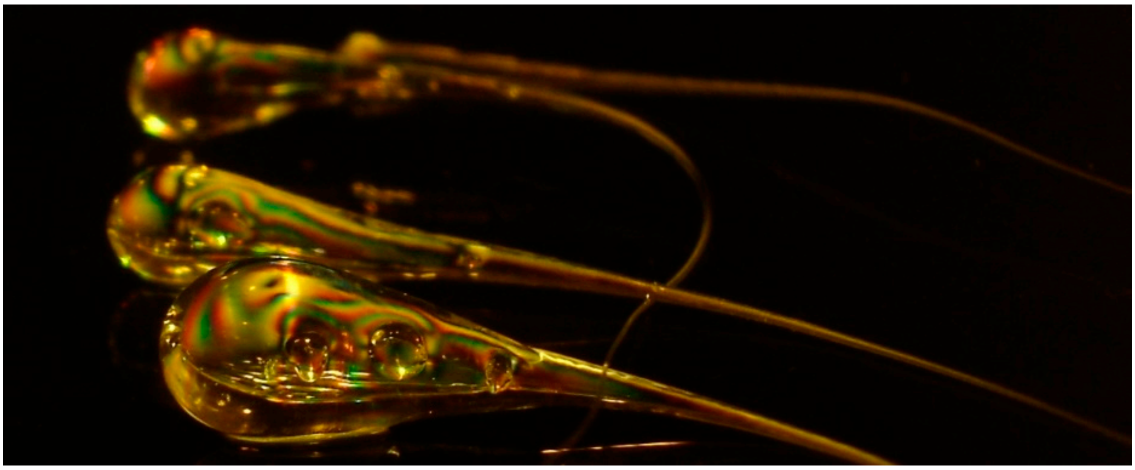


Figure 1. Prince Rupert's drops (from Wikipedia).

2.2. Discovery of the Phenomenon of Hot Luminescence

Ordinary photoluminescence in condensed matter is emitted from an excited electronic state when the vibrational movements in the matter have thermalized. However, a detailed theory of secondary light emission of impurity centers in crystals, which was developed in the Institute of Physics (Presently belongs to the University of Tartu. In the last century, it was the largest (staff about 400) institute of the Estonian Academy of Sciences) in Tartu, indicated that—in addition to the ordinary luminescence and the resonance Raman scattering—there should be an emission named hot luminescence [6–9]. Hot luminescence (HL) typically constitutes less than 1/1000 of the total luminescence emission. The reason is that while the lifetime of the electronic state with respect to the emission of a photon is in the range of nanoseconds or longer, the vibrational relaxation occurs within a few femtoseconds. The first observations of hot luminescence required single photon counting—a little-known technique in those years—and confirmed the theoretical predictions [7]. Afterwards, HL was observed and studied in frozen solutions of rare gases and organic molecules, as well as in molecular crystals [9]. Later, the HL of rare gas crystals was studied in Tartu. In other countries, the HL of semiconductors has been studied most intensively. Reference [6] has been cited 435/388 times The Web of Science finds 191 publications from the years 1980 to 2022, the title and/or abstract of which contain the term “hot luminescence” and which together have been cited about 3600 times.

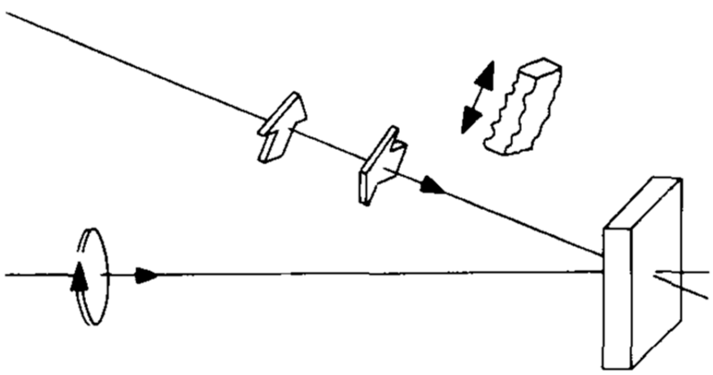
2.3. Discovery of the Phenomenon of Persistent Spectral Hole Burning

Persistent spectral hole burning (SHB) is the frequency-selective bleaching of the absorption spectrum of a material, which leads to an increased transmission (a “spectral hole”) at the selected frequency. The bleaching takes place due to photochemical or photophysical transformations of the molecules that absorb laser light and is persistent at low temperatures. The width of the hole is determined by the laser linewidth and the homogeneous linewidth of the molecules, which in the range of GHz or less at temperatures below 10 K [10–13], while the inhomogeneously broadened whole absorption band is typically 10^3–10^5 times wider. Reference [10] has been cited 490/404 times.

In 1987, in Tallinn, a conference on SHB was organized, and since then, such conferences rotate globally every 2–3 years, the last one being held in Bayreuth (Germany). In addition to [13], several other collective monographs have been issued, e.g., one edited by W. Moerner [14] from IBM Research Division, San Jose, (USA), who was awarded the Nobel Prize in 2014 for his invention of the spectroscopy of single molecules in condensed matter. In addition to Wikipedia, the SHB is also considered in a professional reference book [15]. Based on the SHB, a number of inventions have been proposed and patents issued. The most obvious idea is frequency-selective optical storage: a 10^3–10^5-fold enhancement of the storage density of optical memories thanks to the addition of the spectral dimension. At the end of the last century, several R&D centers (incl. IBM) worked on developing such memory. However, the need for cryogenic temperatures made SHB memories impractical, and the development of flash memories solved the task of dense storage capacity without optics.

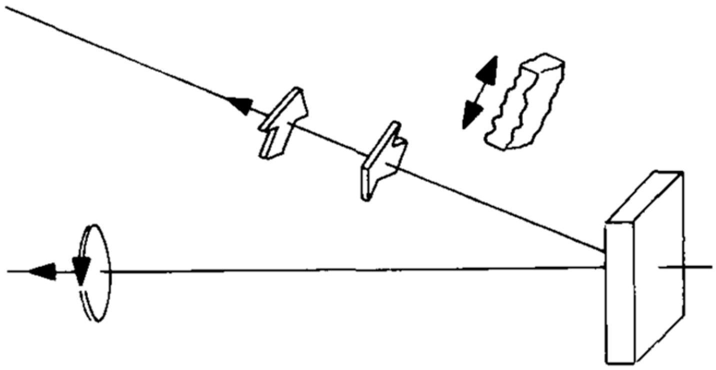
2.4. Invention of the Time–Space Holography

As was shown theoretically and accomplished experimentally in [16,17], a plate made from SHB material memorizes not only the spatial but also the temporal behavior of the incident light, i.e., the interfering signal and the reference plane-wave pulse. If the plate is illuminated by an ultrashort read-out pulse later on, the recorded scene of the ultrashort duration is played back. As shown in subsequent publications, such a generalization of holography is possible not only in the time dimension but also in the behavior of the polarization of the signal [18]. Thus, a complete recording and playback, as well as phase conjugation of any ultrashort (within the femto-nanosecond range) light field, is possible by time–space holography based on the SHB materials at cryogenic temperatures (see Figure 2). The pioneering paper [16] has been cited 144/115 times.



(a)

Figure 2. *Cont.*



(b)

Figure 2. Schematic of recording (**a**) and conjugated reconstruction (phase conjugation) (**b**). The oblique object beam consists of two temporally separated and partly spatially overlapping picosecond pulses of orthogonal linear polarizations. The cross section of the wavefronts of the pulses is shaped by arrow-like transmission masks, while the direction of the arrows corresponds to the polarization plane. Plane reference and reading pulses are of counterrotating circular polarizations. If a phase distorter plate is inserted into the object beam, then the signal will be played back without distortion due to the phase conjugation in the process of reconstruction. Reproduced from [19].

2.5. Contribution to the Development of Methods for the Complete Characterization of Ultrashort Optical Pulses

As is well known, there is no such thing as an oscilloscope for light pulses. Therefore, since the invention of picosecond lasers in the 1970s, a number of sophisticated techniques for the complete (amplitude and phase) characterization of ultrashort optical pulses have been developed in the ultrafast phenomena community. However, typically, they are based on some nonlinear optical phenomenon and require a strong pump and/or reference pulse, and therefore, they are not suitable for the study of weak incoherent pulses that are spontaneously emitted by matter. For the latter purpose, a device was worked out on the basis of a picosecond laser, a streak camera, and a double monochromator of a special subtractive dispersion mount [20]. The device, called a spectrochronograph, enabled the measurement of spectrograms (short-time Fourier transforms) of light pulses with simultaneous spectral $\Delta\omega$ and temporal $\Delta\tau$ resolutions close to the uncertainty principle limit, $\Delta\omega\ \Delta\tau \sim 1$. With this device, picosecond-duration decay times of hot luminescence spectral lines were measured under pulsed excitation, thus proving the nature of hot luminescence as spontaneous emission in the course of vibrational thermalization in the excited electronic state [20]. This paper has been cited 54/58 times. The spectrochronograph has been fruitfully used for decades in studies of photosynthesizing systems, see, e.g., [21] carried out at the Laboratory of Biophysics of the Institute of Physics in Tartu. Recently, in the Institute, a version of a white-light spectral interferometer was also built, which employs photonic crystal fibers in both the signal and reference arms and achieves a few micron spatial and almost one-wave-cycle temporal resolution in measurements of impulse responses of optical elements (see review [22], Ref. 148 therein, and Figure 3).

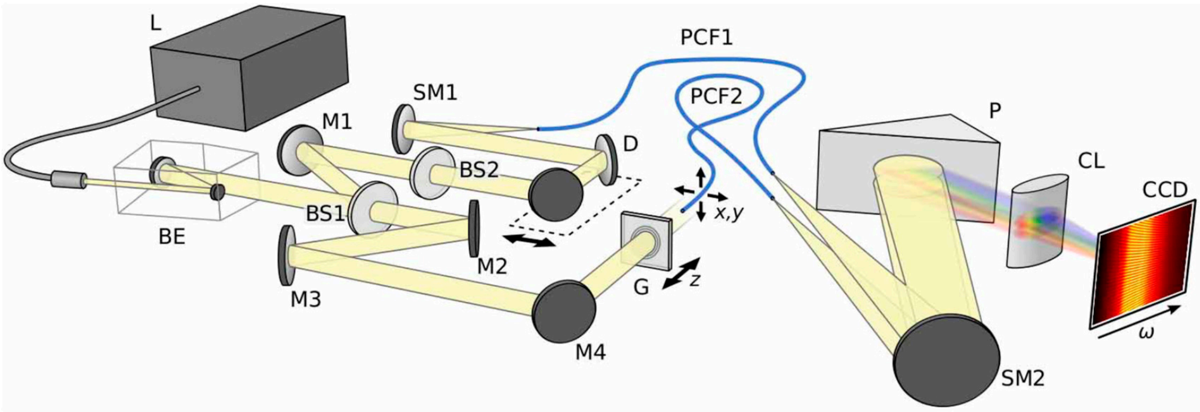


Figure 3. Experimental setup for measuring ultrashort impulse responses of optical elements. L, fiber laser producing white light pulses; BE, beam expander; BS, beamsplitter; M, mirror; SM, spherical mirror; D, variable delay line; G, the optical element under study; PCF1 and PCF2, photonic crystal fibers in the reference and measurement arms, respectively. Interference between outputs of the fibers is analyzed by a spectrometer consisting of reflecting half-prism P, spherical mirror SM2, cylindrical lens CL, and a CCD camera. Reproduced from [23].

2.6. Implementation of Ultrashort Spatio-Temporally Entangled Localized Waves in Optics

Such waves—presently also known as space–time wave packets—constitute spatiotemporally localized (rigidly propagating, non-spreading, and "non-diffracting") solutions to various hyperbolic equations governing acoustic, electromagnetic, and quantum wave phenomena. The first versions of such solutions, where spatial and temporal dependencies were not factorized, were discovered in mathematical physics in the late 1980s, but it remained unclear how and whether at all they could be generated in reality. The realizability of them in optics was first demonstrated in air [24] and in glass [25] for the example of the so-called Bessel-X pulse, which is a simple representative of superluminally propagating localized waves [26]. The pioneering paper [24] has been cited 504/327 times. It was shown that monochromatic non-diffracting Airy waves—intensively studied since the beginning of the century—have ultrashort pulsed versions [27]. Thanks to the publication of about a hundred journal papers and conference presentations, the Laboratory of Physical Optics in Tartu became one of the leading research centers for the study of these wave packets and contributed review chapters to the first two collective monographs in the field, published in 2008 and 2013, respectively [28,29]. During the second decade of the century, the College of Optics and Photonics of the University of Central Florida became a center of very intensive study of this subject (Their recent thorough paper, [30] reviews the historical development, describes the new experimental approaches, and enumerates the various potential applications in the field).

2.7. Development of Methods for Measurements of Top-of-Canopy Reflectance of Forests and for Vegetation Radiative Transfer Modeling

Remote sensing satellites measure large areas at regular intervals and provide the only means for Earth observation on a global scale. The remotely sensed data can be used for assessing the parameters of the terrestrial targets at the time of the satellite overpass or for estimating climate change and other long-term trends from the time series of the satellite data. Interpretation of the data is based on the radiative transfer models that describe how photons interact with terrestrial objects and the atmosphere between the objects and the satellite sensor. Radiative transfer models for vegetation, and in particular for forests, as well as the corresponding measurement equipment, have been developed for decades in the Tartu Observatory (see [31–33] and references therein). Reference [31] has been cited 404/233 times. The best possible field data are required for the development and validation of such models [33]. A series of lightweight, autonomous spectrometer systems named UAVSpec were developed in the Tartu Observatory for measurement of spectral and angular properties of forest reflectance from a low-flying airborne platform.The systems consist of a hyperspectral radiometer based on a miniature spectrometer module, a GPS and tilt sensor for georeferencing the measurements, and an RGB camera. The angular distribution of reflectance was measured with a linear photodetector array equipped with a bandpass filter. The availability of high-quality field data for vegetation radiative transfer model validation is very limited; three out of six scenarios used in the fourth phase of the international radiative transfer model intercomparison exercise were based on measurements of Estonian forests [34].

3. Optics Companies

After WWII, the design and production of optical instruments began in the 1960s at the Institute of Physics and Astronomy in Tartu, which belonged to the system of the Soviet Academy of Sciences through the Estonian Academy of Sciences. The production included vacuum ultraviolet double monochromators—the first such ones in the world (its next, further elaborated version received a patent in the USA (No. 4,523,845))—for research laboratories and a series of spaceborne spectrometers for Soviet space stations 'Salyut-4', 'Salyut-7', 'Kosmos-1686', and 'Mir' (The results were published, e.g., in [35]).

In the 1980s, diode lasers for the near infrared region were developed in the Laboratory of Semiconductor Physics (whose successor is the Laboratory of Thin Film Technology) of the Institute of Physics. The lasers were based on double heterostructures. At that time, the wavelength of 1.74 μm emitted by these lasers at temperatures up to 305 K was the highest emission wavelength obtained in the world from diode lasers working in the CW mode at room temperature.

3.1. Laser Companies

Also, in the 1980s, powerful excimer and dye lasers were designed in the Institute of Physics and in the so-called special construction bureau, which was actually a design and production unit of the Estonian Academy of Sciences with several hundred staff of engineers and workers. In addition to supplying these lasers to a number of research institutions in Estonia and Russia, the lasers were also sold in the East-European market. Moreover, allegedly, the first orbital lidar, SEZON, was designed and made for the Soviet space station MIR.

After regaining independence in 1991, several spin-off laser companies arose. Some of them sold their products to the USA (NASA, US NAVY, Los Alamos National Laboratory) and to Japan. The company Estla in the Tartu Science Park has survived to this day, and in addition to lasers, its products include laser-based detection systems for biology, environmental monitoring, and material testing.

3.2. Companies Developing Deep-Tech Cameras for 3D Vision

LightCode Photonics, a spin-off of the University of Tartu, is a deep-tech company that was founded in 2020 by four PhD-grade innovators from the Laboratories of Physical Optics and of Physics of Ionic Crystals in the Institute of Physics. They build dynamic pixel 3D cameras, whose unique sales point is the ability to detect small (10 times smaller than the pixel size) and dark objects at up to 20 m distance. The company has received three awards: Tartu Science Park's Company of the Year, the title of the most outstanding start-up company by the sTARTUp Day, and the main prize of the prestigious MIT Enterprise Forum Greece program for technology companies.

The Space Technology Department at the Tartu Observatory, the University of Tartu, develops and tests space instruments for various space missions and also conducts research and development activities for industrial clients. For example, they developed and flight-qualified a Lunar lander stereo camera system for the SAMPLR experiment in the NASA CLPS program; they are developing a camera system for ESA's (the European Space Agency) Comet Interceptor mission (OPIC); they are working on the first private planetary mission series with MIT (Venus Life Finder, now called Morningstar); and they are developing an optical acidity sensor for it. They are also developing systems that utilize camera data from remote sensing and autonomous platforms for both industrial autonomous robots and planetary rovers (they recently concluded a project to develop a mobility planning tool for Lunar rovers for ESA).

3.3. Companies of Monitoring and Testing Instruments

Laser Diagnostic Instrument's main product family is Remote Optical Watcher (ROW), for remote online monitoring of water quality and petroleum products' contamination utilizing the fluorescence properties of organic compounds. Currently, they have more than 600 installations in more than fifty countries around the world. Their laser-based device for the treatment of tuberculosis was awarded the golden medal at the Brussels Eureka 51st World Exhibition of Innovation, Research, and New Technology 2002 in Belgium.

LDI Innovation produces sensors, lidars, and compact excimer lasers. The company has been listed among the top ten European companies that are at the forefront of providing sensor technology solutions and transforming businesses. They also have acknowledged results in combining airborne hyperspectral imagery and laser-induced fluorescence technologies for remote sensing of oil spills in the sea [36] (cited 68/50 times).

Ldiamon's (Tartu Science Park) main products are online optical sensors that utilize the optical spectrophotometric methods for the measurement of the light absorbance of urea and food freshness sensors.

Optofluid Technologies develops sensors for real-time and online dialysis quality monitoring.

Interspectrum is an experienced spin-off company (founded in 1991) at the Tartu Observatory that develops and produces a variety of FTIR-spectrometers (Fourier-transform infrared) that are used in many fields, including analytical chemistry, material research, medical research, food science, applied physics, and environmental research.

Difrotec's (Tartu Science Park) main product is a phase-shifting point diffraction common path interferometer for ultra-high-accuracy (0.6 nm) measurements of surface form and transmitted wavefront quality. They have a USA patent No. 10,247,359 and a European patent No. EP3187820. The company has collaborated with the ESA (European Space Agency), Huawei (China), and Brookhaven National Laboratory (USA).

Glasstress has commercialized the pioneering research results on photoelasticity, see [1–5] in part I. The company's products include three types of portable polariscopes for internal stress measurement in sheet glass, thick windows, and round glass objects. In recent decades, their polariscopes have been installed in production lines and quality control and improvement laboratories of a number of global players in the glass industry: Bucher Emhart Glass (Switzerland, USA)—the world's leading supplier of advanced technologies for the manufacturing of glass containers; SISECAM (Turkey)—one of the largest glass manufacturers in Europe; Verrerie Crystallerie d'Arques (France, USA, China)—produces glass tableware in 12 locations around the globe; Asahi Techno Glass Corporation (Japan) and Philips (Netherlands)— in the years when they mass-produced cathode-ray tubes for TV sets. As a service, Glasstress offers an analysis of the stresses in glass products (bottles, drinking glasses, electric lamps, optical fiber preforms, panels of architectural glass, automotive glazing, etc.). The company has also regularly organized international summer schools on glass stress measurements.

With the company's instruments and experience in residual stress 3D measurements, the mystery of Prince Rupert's tadpole-shaped drops—while the head of the drop is so strong that it withstands the impact of a hammer, the tail is so fragile that bending it with fingers causes the entire droplet to instantly disintegrate into a fine powder—was solved in collaboration with researchers from the Purdue University, see [37].

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