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Quantum Photonics: Pioneering Advances and Emerging Applications

Springer

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Preface

The word “quantum” became popular not only in physics, but in a much wider world: today’s general public is intrigued by extremely powerful quantum computers, quantum teleportation, and secure quantum communication in space. Usage of “quantum” in popular movies, TV shows, newspapers, and some consumer goods made it saturate the air for almost everybody, although often with the meanings different from those in physics.

The unique purpose of this book is to bring together the largely unreported history of experiments with single “light quanta” (photons) and map it with its modern manifestations as one of the key drivers to the vibrant scientific field of quantum photonics. We seek to convey to the readers the state-of-the-art advances of modern developments in quantum photonics and nonlinear optics from the leading groups throughout the world. The book also familiarizes the scientists, teachers, and students with the earliest experiments on single-photon and nonlinear optics from a time when both lasers and today’s light detectors did not yet exist, and the photographic plate or the human eye served as single-photon detectors. As a result, this book consists of two parts: (i) *Modern Quantum, Nano- and Nonlinear Photonics*, and (ii) *Historical Works: Single-Photon and Nonlinear Optical Experiments in the Pre-Laser Era* complimented with reprints and translation into English of some pioneering experimental papers. The book contains contributions of researchers from Australia, Canada, France, Germany, Hungary, Israel, Japan, Russia, Singapore, UK, and USA.

In this Preface, we clarify terminology and give relevant brief historical information. We also highlight the chapters of each of two parts of the book.

Terminology with Some Historical Highlights

Light Quanta (Photons)

In the third online edition of the Oxford English Dictionary (OED, December 2007), the first usage of the word “quantum” in English (borrowed from Latin) is dated back to 1567 (“… the body of Christe in the Sacramente is *quantum* …”). Initially, this word had meaning of something that has quantity or total amount of quantity and was found chiefly in philosophy-related manuscripts or in law literature (with reference to amount of money).

According to the same edition of the OED, the usage of “quantum” in physics was recorded in 1870 (Nature **1**, p. 306) in a sense of quantity (“a certain quantum of the electric fluid”). Lord Kelvin also used “quantum” in a similar sense in both his 1902 and 1904 papers.

The modern meaning of the “quantum” concept in physics (a discrete quantity of electromagnetic energy proportional in magnitude to the frequency of the radiation, or any other physical discrete quantity (e.g., momentum or electric charge)) was born in the early twentieth century, owing to two classic German papers by Max Planck [1] and Albert Einstein [2]. We also would like to mention experiments of Millikan on the photoeffect confirming Einstein’s prediction [3] and Compton on inelastic X-ray scattering by electrons [4] after which the concepts of early quantum theory were accepted by the scientific community. See also the 1954 Nobel lecture by Glauber[1] on the history of light quanta [5].

Planck

Planck’s talk of December 14, 1900, and its publication [1] was later recognized as the turning point in the history of physics and currently is considered widely as the birth of quantum mechanics. Deriving oscillators’ entropy in the spectrum of blackbody radiation (distribution of a given energy among a set of oscillators producing the heat radiation emitted by black bodies), to satisfy experimental data, Planck introduced “energy elements” (Energieelemente, in German). He postulated that an energy E of the N resonators of frequency v “to be composed of a very definite number of finite equal parts and we use thereto the constant of nature $h = 6.55 \times 10^{-27}$ erg s”. He continued further: “This constant multiplied by the common frequency v of the resonators gives the energy element ϵ in erg, and dividing E by ϵ we get the number P of energy elements to be distributed over the N resonators” [1]; see also [6].

Einstein

Einstein was the first to recognize in 1905 that the discontinuity of Planck’s theory of blackbody radiation is not only a formal necessity for fitting the equation with the experimental data, but leads to new physics. Einstein started first the usage

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[1] Roy Jay Glauber, one of the founding fathers of quantum optics and its “icon” through his quantum theory of optical coherence, widely cited in this book (Chaps. 1, 3, 4 and 19) passed away while it went to print. Glauber will stay in our memory as Dr. Quantum Optics (coined by J. Eberly).

of the word “quanta” (plural) in the meaning of modern physics [2]: “Indeed, it seems to me that the observations regarding “blackbody radiation”, photoluminescence, production of cathode rays by ultraviolet light, and other groups of phenomena associated with the production or conversion of light can be understood better if one assumes that the energy of light is discontinuously distributed in space. According to the assumption to be contemplated here, when a light ray is spreading from a point, the energy is not distributed continuously over ever-increasing spaces, but consists of a finite number of energy quanta (Energiequanta, in German) that are localized in points in space, move without dividing, and can be absorbed or generated only as a whole.” In this paper [2], in the photoelectric effect section, he proposed a linear relationship between the maximum energy of electrons ejected from a surface and the frequency of the incident light. The slope of the line which did not depend on the substance was Planck’s constant. Verification of Einstein’s law for the energies of the photoelectrons came only in 1914–1916 by Millikan experiments, although even after them some doubts about the quantized nature of light persisted in scientific community, and only after Compton’s discovery in 1922 of X-ray quanta scattering by electrons obeying the same rules as the particle scattering, Einstein’s theory of light quanta was accepted.

Photon

The name “photon” is derived from Greek (φώτο = photo = light) and the “-on” at the end of the word was introduced in the twentieth century [7]. “Photon” as an alternative name for Einstein’s quantum of light became preferable by the mid-1930s [7]. Although it was used by several independent researchers earlier (see [7]), this word became synonymous with quantum of light only after the paper of Gilbert Newton Lewis of 1926 [8] in spite of its different meaning from Einstein’s light quantum: “… I therefore take the liberty of proposing for this hypothetical new atom, which is not light but plays an essential part in every process of radiation, the name photon” [8]. In our book, we have a chapter about Lewis’ contribution to nonlinear optics with a short biography of this outstanding scientist. According to [7], Arthur Holly Compton promoted the new term “photon.” In his 1927 Nobel lecture Compton wrote: “Here we do not think of the X-rays as waves but as light corpuscles, quanta, or, as we may call them, photons.” He also used it in popular literature.

Leonard Thompson Troland (famous American physicist, engineer and psychologist, president of the Optical Society of America (1922–1923)) first coined the word in 1916 (see [7] for more details and references therein), but he used it as a unit for the illumination of the retina. Five years later, it was independently introduced by the Irish physicist John Joly, professor of geology and mineralogy who was also interested in vision. What Joly called a “photon” was the minimum stimulus required to produce a signal in a fiber of the optic nerve. Then, in 1925, a French biochemist, biophysicist, and physiologist, René Wurmser (who was nominated twice for a Nobel Prize in Chemistry), in his paper about photochemical reactions relating to the role of chlorophyll in photosynthesis, wrote that “the activation of a molecule, in the sense of J. Perrin, demands the absorption of an integral but variable number of photons.” Like Wurmser, but in a very different context, his compatriot, physicist Frithiof (Fred) Wolfers in his hypothesis also related to Perrin’s idea of molecular resonance (“induction moléculaire,” in French) suggested: “I shall use the name photons for the projectiles that supposedly transport radiant energy and possess the character of a periodic frequency v (atoms of light). I then suggest that the photons may be repelled by the atoms of matter when they pass them closely … One may imagine that the repulsion is due to a kind of resonance between the photons and the resonators …” [7].

Photonics

In the current professional literature, “photonics” is used almost synonymously with the term “optics,” referring equally to both science and applications [9]. The phrase “optics and photonics” is used in [9] to capture light’s dual nature as:

- a propagating wave, like a radio wave, but with a much higher frequency;
- a collection of photons, with potential as a transformative field similar in impact to electronics.

According to the OED, the term “photonics” was mentioned already in 1952 in the Journal of the British Interplanetary Society: “From the fundamental domains of photonics, electronics, … and physical chemistry, our interest passes … to aerodynamics and the physics of solid bodies.” Independently, the term “photonics” (фотоника in Russian) was introduced in 1967 in the book in Russian [10] “Photonics of Molecules of Dyes and Related Compounds” of the Soviet academician Alexander N. Terenin. A European Commission CORDIS states that the term “photonics” was coined in 1967 by Pierre Aigrain [11], a prominent French physicist, a foreign member of the National Academy of Sciences (USA, since 1974): “Photonics is the science of the harnessing of light. Photonics encompasses the generation of light, the detection of light, the management of light through guidance, manipulation, and amplification, and most importantly, its utilization for the benefit of mankind.” In 1975, the book “Photonics” [12] (Proceedings of 1973–1974 years’ talks and a 1974 year conference) edited by M. Balkanski and P. Lallemand was published in Paris in which this term was used by analogy with electronics, describing the application of the photon to the transmission of information, and included such topics as photon beam production, waveguiding, deflection, modulation, amplification, image processing, storage, and detection [13]. This book contains an explanatory note of Balkanski “Photonics: perspective in 1974” and Aigrain’s chapter in French “La photonique, technique de demain.” The term began to be seen in print in English around 1981 in press releases, annual reports of Bell Laboratories, and internal publications of Hughes Aircraft Corporation and in the more general press [9].

In the last decades, with development of integrated, nano-, biophotonics, free-space optical communication, and with the impact increasing of photonics on the national economies, the concept of “photonics” acquired a broader sense [9, 14]. It comprises also light–matter interaction, including nonlinear optical interaction and extreme photonics. The twenty-first century will depend as much on photonics as the twentieth century depended on electronics (see the website of the International Year of Light (2015) [15]). In the book, we are using “photonics” in this broader sense as, for instance, in Ralf Menzel’s book, page 2 [16].

Part I. Modern Quantum, Nano- and Nonlinear Photonics

This part of the book consists of ten chapters and opens with Chap. 1 by Aspect and Grangier on the first single-photon sources and single-photon interference experiments. The authors emphasize the difference between “single-photon wave packets” and attenuated classical light pulses or light beams and describe the single-photon source developed by them in the mid-1980s (heralded single-photon wave packets, based on pairs of photons emitted in a radiative cascade). They also define the quantitative criterion of “anticorrelation” they use in distinguishing single-photon wave packets from attenuated pulses. In addition, the first single-photon interference experiment performed by the authors with their heralded source illustrates the notion of wave–particle duality. Brief overviews are also provided for both the first interference experiments in feeble light at 10^2–10^7 photons/s, and further developments in sources of single photons, heralded or on-demand, as well as in wave–particle duality experiments, in particular Wheeler’s delayed-choice experiment.

Mirhosseini, Lundeen, and Boyd (Chap. 2) provide an overview of recent progress in the tomography of structured light with an emphasis on the method known as direct measurement of the quantum wavefunction. Direct measurement provides a scalable and easy-to-implement approach for characterizing the transverse structure of single photons. This protocol is particularly attractive in light of the emerging role of high-dimensional optical states as a resource for encoding quantum information. This chapter presents a summary of various implementations of this technique that aim to characterize the spatial degree of freedom of the optical field.

Strekalov and Leuchs (Chap. 3) overview nonlinear interactions and non-classical light. This chapter includes the definition of non-classical light and basic examples and reviews some of the most prominent applications of non-classical light as well as the most common sources of non-classical light including physical systems of various sizes and complexity (ranging from single atoms to optical crystals and to semiconductor lasers). The authors also outline the trends in the field and the new cross-disciplinary approaches and techniques of generating non-classical light.

Lukishova and Bissell (Chap. 4) review room-temperature single-photon sources with photons exhibiting antibunching, including the authors’ results on single-photon sources with definite circular and linear polarizations. Single, “giant”, colloidal, semiconductor nanocrystal quantum dots and dot-in-rods, diamond color centers (both bulk and nanodiamonds), and trivalent rare-earth ions offer the best photostability (longest operating time) in room-temperature excitation. This review highlights nanophotonic aspects of the problem, describing room-temperature single-photon sources based on these emitters and some new, stable, single emitters. Methods for emitter fluorescence enhancement (microcavities, including photonic bandgap, Bragg reflector and chiral liquid crystal microcavities, plasmonic nanoantennas, metamaterials), and the alignment of anisotropic single emitters with the help of liquid crystals are described and compared.

In Chap. 5, Victora, Kaneda, Bergmann, Wong, Graf, and Kwiat present an overview of time-multiplexing methods and time-bin qubits for quantum information processing with photons including applications of time-multiplexing techniques for more efficient single- and multiphoton sources, improved detectors, and high-bandwidth quantum memories, as well as enhanced applications such as quantum random walks and entanglement swapping. The results (by the authors) on experimental demonstration of a time-multiplexed, heralded, single-photon source are included.

Krivitsky and Volkov (Chap. 6) address the question of how fundamental photon fluctuations are perceived by a live visual system. The discussion is focused on photoreceptor cells within the eye, known as retinal rod cells. Rod cells provide vision under low-light conditions and are sensitive at a single-photon level. The authors review experiments on interaction of the rod cells with light sources of different photon statistics, including coherent, pseudo-thermal, and single-photon sources. Accurate control over photon statistics of light stimuli, combined with the technique for the readout of rod cells' response, enables precise and unambiguous characterization of intrinsic features of the visual system at single and discrete photon levels.

Chapter 7 by Fang, MacDonald, and Zheludev is devoted to controlling light with light via interference on planar photonic metamaterials. Planar photonic metamaterials—ultrathin media with nanoengineered optical properties—can realize the full potential of this concept to change optical data processing paradigms, spectroscopy, and nonlinear optics. Thin-film media can, if the film is much thinner than the light wavelength, lead to controllable energy exchange between incident and scattered waves and thereby to a plethora of new technological opportunities. This chapter describes how coherent interactions in metamaterials can facilitate nonlinear light-by-light control functions with THz bandwidth at arbitrarily low intensities.

Krasavin, Ginzburg, and Zayats (Chap. 8) review nonlinear plasmonics and plasmonic metamaterials. Plasmonics as a tool for tailoring and enhancing nonlinearity (coherent and Kerr-type nonlinearities, plasmonic metals as nonlinear materials), nonlinearities in plasmonic nanostructures, harmonic generation in plasmonic nanostructures, Kerr-type nonlinearity and ultrafast all-optical switching including nonlinear plasmonic crystals and optical bistability, nonlinear plasmonic metamaterials, epsilon-near-zero metamaterials, nonlinear surface plasmon polaritons are described in this chapter.

Makarov, in Chap. 9, concentrates on nonlinear optics with elliptically polarized singular beams and short pulses in media with spatial dispersion. The conditions of appearance and the behavior of polarization singularities in the cross section of a light beam, arising due to nonlinear interaction of elliptically polarized laser beams with a medium with nonlocality of quadratic and cubic optical responses, are discussed. The formation dynamics and propagation features of polarization singularities, including pairwise creation and annihilation, for sum-frequency and second harmonic generation, beam self-action and interaction, and other nonlinear optical processes are presented. The author also discusses the effects accompanying the propagation of ultrashort (few oscillations) elliptically polarized light pulses in a nonlinear isotropic gyrotropic medium with frequency dispersion.

Zheltikov (Chap. 10) outlines ultrafast nonlinear optics in the mid-infrared. Recent breakthroughs in the generation of high-intensity, ultrashort laser pulses in the mid-infrared offer new approaches. This spectral range is unique in many ways, giving rise to new regimes of high-field nonlinear optics. Within this region, many molecular bands are located, drastically enhancing the coupling between the field and molecular motions. Electrons driven by intense field of ultrashort mid-infrared pulses acquire unusually high ponderomotive energies within a fraction of the field cycle. In addition, in this region the threshold power of self-focusing, proportional to square of the radiation wavelength, significantly increases. Consequently, much higher peak powers can be transmitted in a single laser filament in the mid-infrared range in comparison with the visible and near infrared, without losing beam continuity and spatial coherence.

Part II. Historical Works: Single-Photon and Nonlinear Optical Experiments in the Pre-Laser Era

This part of the book consists of nine chapters and contains both reprints or translations into English of experimental papers on the first quantum and nonlinear optical experiments during the pre-laser era as well as papers about the scientists who carried out these experiments (or their short biographies). The experiments of the researchers from different countries are included on the observation of the first interference fringes in a faint light, first light pressure measurements, first nonlinear optical experiments (saturation of absorption or luminescence) and their usage in practical devices, first experiments on sensitivity of a human eye to a faint light excluding physiological fluctuations smearing the results, first observation of statistical structure of interference field and independent fluctuations in two split coherent beams by a human eye in a faint light, and first photon-correlation measurements in split coherent beams using photomultipliers.

Chapter 11 by Lukishova includes Taylor's 1909 paper as well as his short biography. This paper is the first-reported experiment on interference fringes with very faint light. The light power in Taylor's experiment was 5 x 10^{-6} erg/s ($\sim 10^6$ photons/s) in a region of interference. Photographic plates were used for registration, and the maximum exposure time was about 3 months without changing the contrast of fringes. This experiment was suggested by Sir Joseph J. Thomson. Robert Millikan in his Nobel lecture [3] referred to the Thomson–Planck–Einstein's concept of localized radiant energy (in its most general form introduced by Thomson in 1903).

The next two chaps. (12 and 13) contain papers of 1901 on the first experiments on measuring the light pressure, which were carried out independently and reported almost simultaneously by a Russian scientist, Lebedev (1900, August), and two Americans, Nichols and Hull (1901, August). These chapters begin with papers by Masalov about Lebedev's experiments and by Garmire about Nichols and Hull's experiments and the accuracy achieved at that time. The works of Lebedev and Nichols and Hull are frequently cited in the current scientific literature, e.g., on laser cooling and trapping as well as on cavity optomechanics.

Chapter 14 is devoted to Vavilov's contributions to photonics. It contains translations into English of parts of his two key papers: on the first nonlinear optical experiment (saturation of absorption in uranium glass at $\mathrm{kW/cm^2}$ of spark light intensity, 1926) and on the sensitivity of the human eye to low-light level (1933). An original reprint of one of his papers in English of 1943 as a development of 1933 year work is also included. Using the human eye as a detector and flashes of faint light at eye's sensitivity threshold ($\sim$40–50 "green" photons on the retina per flash in these measurements), Vavilov clearly observed independent intensity fluctuations of two split coherent beams, but sometimes two split beams were seen simultaneously (1933). He also studied a statistical structure of interference pattern. This chapter also contains the paper by Lukishova about Vavilov's contributions to photonics, specifically Vavilov–Čerenkov radiation (Vavilov was Čerenkov's thesis advisor, but had passed away when this effect deserved the 1958 Nobel Prize in physics).

Lewis, Lipkin, and Magel's 1941 paper on nonlinear optical effects (saturation in absorption and phosphorescence) is outlined in Chap. 15 by Lukishova. The authors investigated a fluorescein-doped boric-acid glass characterized by low saturation intensities. (In a recent publication [17] on the same material, the following numbers are reported: absorption saturation intensity of $\sim 15\ \mathrm{mW/cm^2}$ and a nonlinear susceptibility $\chi^{(3)}$ as large as ~ 1 esu, as compared to $\sim 10^{-12}$ esu for the commonly used Kerr liquid CS_2). This chapter also contains Lewis' biography.

In Chap. 16 Stroud describes the nonlinear optical device of 1941 of the Institute of Optics, University of Rochester, based on saturation in luminescence. The Icaroscope by O'Brian was used by pilots during the Second World War. An original publication of O'Brian is reproduced.

In Chap. 17 by Lukishova, we included a reprint of the highly cited, 1941 paper by Hecht, Shlaer, and Pirenne on the sensitivity of the human eye at low-light level. Hecht et al. used a method similar to Vavilov's experiments of 1933–1942, and both groups independently arrived at similar results. In the same chapter, we also reprinted some excerpts from biography of Selig Hecht, member of the National Academy of Sciences (USA, since 1944).

The next two chaps. (18 and 19) are devoted to the first photon-correlation measurements using photomultipliers. Chapter 18 by Varró is devoted to the Hungarian scientist Jánossy who with his co-workers for the first time used photomultipliers and the photon-counting technique for photon-correlation measurements. Translation into English of paper of 1954 of Ádám, Jánossy and Varga is added to this chapter. This part of their study is considered as the forerunner to the Hanbury Brown- and Twiss-type correlations with visible light, although Jánossy did not observe correlations in two split coherent beams. Chapter 18 begins with a biography of Jánossy. Chapter 19 by Lukishova and Tango is devoted to the Hanbury Brown–Twiss effect of 1956 on observation of positive correlations between two photomultiplier signals from a split-beam optical source. The history of its discovery is reprinted from the book of R. Hanbury Brown "Boffin: A Personal Story of the Early Days of Radar, Radio Astronomy and Quantum Optics. " The short biographies of both researchers are also included. Tango who worked with Twiss wrote his biography for this book.

In conclusion, we believe that this book will be useful for academics, researchers, engineers, and students in many disciplines who hope to learn more about the history of quantum and nonlinear optics and upcoming trends in quantum photonics and nonlinear optics. Finally, we would like to thank all contributors who have found the time, energy, and enthusiasm to write these chapters. We highly appreciate the work of the translators of some papers into English. We thank American Institute of Physics, American Physical Society, Optical Society OSA, Cambridge Philosophical Society, the Rockefeller University Press, P. N. Lebedev Physical Institute, Russian Academy of Sciences (RAS), RAS Nauka Publisher (Moscow, Russia), S. I. Vavilov Institute for the History of Science and Technology of RAS (Moscow, Russia), Australian Physical Society, University of Rochester Library Archive, the Russian journal Uspekhi Fizicheskikh Nauk (Physics-Uspekhi), American Institute of Physics Emilio Segrè Visual Archives, Cavendish Laboratory (University of Cambridge), the Radio Society of Great Britain, Marion Hanbury Brown, and Norbert Kroo for help and permission in publishing images, journal reproductions, or text excerpts.

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