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(Invited) Story behind the Nonlinear Fiber Optics book

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ABSTRACT

The first edition of my book *Nonlinear Fiber Optics* was published in 1989. It was followed by several editions, the sixth one appearing in 2019. I have been often asked what motivated me to write a book on nonlinear fiber optics. The editors of this special issue have invited me to write an account of my activities during the 1980s that led to the publication of the book. After explaining how I entered the field of nonlinear fiber optics, I briefly discuss my research activities that led me to consider writing a book in this area. I also provide a few interesting details related to the writing and submitting of a camera-ready printed copy of the book's manuscript.

1. Introduction

The first edition of my book *Nonlinear Fiber Optics* was published in 1989 by the science publisher Academic Press, acquired later by Elsevier. The reviews and other feedback on this book indicated that it was liked and used by the scientists and engineers working in the areas of fiber optics, nonlinear optics, and optical communications. Because of its success, the *Nonlinear Fiber Optics* book has gone through multiple editions over a period of 30 years, the sixth edition appearing in 2019 [1]. The book has also been translated into several languages including Russian, Chinese, and Japanese. I have been often asked what motivated me in the 1980s to write a book on nonlinear fiber optics. The editors of this special issue have provided an opportunity by inviting me to write an account of my research activities during the 1980s that led me to the conception of such a book.

As would be expected for any active research area, each new edition of *Nonlinear Fiber Optics* underwent substantial revisions to ensure that the new research material was included. For example, its second edition, published in 1995, added chapters on fiber Bragg gratings, fiber amplifiers, and fiber lasers. When I started working on the third edition around 2000, I realized that the new material will increase the book's size so much that it will contain more than 800 pages. I decided to split the material into two books, each containing about 400 pages. One book focused on the fundamental aspects of nonlinear fiber optics and retained the original title. The other was devoted to its applications and was published in 2001 under the title *Applications of Nonlinear Fiber Optics*.

I started thinking about the fourth edition of *Nonlinear Fiber Optics* in 2006. With the advent of new types of highly nonlinear fibers, known as photonic crystal fibers, holey fibers, and micro-structured fibers, much new research has been done in the period ranging from 2000 to 2006, especially in the emerging area of supercontinuum generation. It was clear to me that considerable material must be added to the book if it had to satisfy its original mission of providing comprehensive coverage in the area of nonlinear fiber optics. Indeed, the fourth edition of *Nonlinear Fiber Optics*, published in 2007, was considerably thicker with three new chapters.

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The fifth edition of *Nonlinear Fiber Optics* appeared in 2013 with more material added to include the research results published from 2007 to 2012. At that time, I thought that would be the last edition of this book. However, I was wrong as I failed to anticipate the emergence of multimode nonlinear optics based on graded-index fibers. By 2018, so much new research has been carried out that I was forced to consider another edition of the *Nonlinear Fiber Optics* book. The sixth edition was published in 2019 with a new chapter on the nonlinear effects in multimode fibers.

2. Employment at Bell Labs

In the year 1982, I had the fortune of joining Bell Labs, known as AT&T Bell Laboratories at that time and famous worldwide for its invention of the transistor, among other things. Telecommunication systems based on optical fibers were commercialized by AT&T just a year earlier. However, the first-generation of these systems employed lasers operating at wavelengths near 800 nm and transmitted data at relatively low bit rates of under 0.1 Gbit/s over multimode graded-index fibers [2]. Moreover, high losses of silica fibers at this wavelength required signal's regeneration after every 10 km or so. It was realized that moving to a wavelength near 1300 nm would reduce both the fiber's loss and its group-velocity dispersion, resulting in longer regeneration lengths and higher bit rates for the second-generation lightwave systems [3]. However, this change required the development of new semiconductor lasers based on the quaternary InGaAsP material. I was hired by the department responsible for the development of such lasers at Bell Labs and I was supposed to work only on this topic.

The working environment at Bell Labs was extraordinary in many respects, one of which being the presence of famous scientists in different areas of science and engineering. I was introduced to P. W. Anderson, who was well-known for his work on "Anderson localization" and has received the Nobel Prize in 1977 [4]. I started hearing about Akira Hasegawa, who predicted in 1973 the formation of solitons inside optical fibers [5], and about Linn Mollenauer and Roger Stolen, who observed such solitons in a 1980 experiment [6]. One day during lunch break, someone pointed to me the place in Bell Lab's cafeteria where Hasegawa was having his lunch. His office was also not very far from my office, as we both worked at the same Murray Hill location of Bell Labs in New Jersey. Even though I found the subject of solitons fascinating, I did not pursue it further because I was busy with my work on InGaAsP semiconductor lasers and was also writing a book about them with my coauthor Niloy Dutta [7].

The situation changed in the year 1985. One day, Mary Potasek, a scientist working at a different location of Bell Labs, came to my office to discuss the problem she was working on. That was a chance encounter as we have not met before. Mary's problem was related to the propagation of short pulses in optical fibers. I told her that I had little expertise in that area. To my surprise, she still thought that my work on lasers was relevant enough to her problem that we could collaborate on it. This collaboration forced me to learn about the nonlinear effects in optical fibers quickly, and we ended up publishing several papers together. To this day, I give credit to Mary for introducing me to the nonlinear phenomena in optical fibers. Had she not wandered into my office looking for a collaboration, it is entirely possible that I would not have entered the field of nonlinear fiber optics!

My first paper in the area of nonlinear fiber optics was published in 1986 with the title "Analytic and numerical study of pulse broadening in nonlinear dispersive optical fibers" [8]. Another paper soon followed in the journal Physical Review A with the title "Nonlinear pulse distortion in single-mode optical fibers at the zero-dispersion wavelength" [9]. Mary Potasek was my coauthor on both of these papers. My main contribution was to develop a Fortran code for solving the nonlinear Schrödinger equation (NLSE) based on the split-step Fourier method. I was used to writing computer codes for my work on lasers and had used the split-step Fourier method for propagation of optical beams inside laser resonators. I employed the NLSE code extensively to study how solitons formed in optical fibers under realistic conditions and what happened to them near the zero-dispersion wavelength, where the effects of third-order dispersion became relevant.

I should mention that computers were much slower in 1985 compared to those available now. Even though personal computers (PC) had been introduced in 1982, and I had one in my office, it had no hard drive and its memory capacity was considerably less than one Megabyte. I used this PC as a terminal to connect to a mainframe computer and downloaded the data after each run of the Fortran code. However, I could not find any decent graphics package for plotting the data (Matlab was not available to me at that time). I remember writing a computer program for plotting the data and printing the plot using a dot-matrix printer. Its quality was so low that I had to use an internal drafting service to produce figures for my papers.

3. Conception and writing of the book

By 1987, I was feeling confident enough that I decided to work alone on the topic of modulation instability. More specifically, I investigated how the nonlinear phenomenon of cross-phase modulation could induce modulation instability in the normal-dispersion region of an optical fiber [1]. This work was published in August 1987 in the high-impact journal Physical Review Letters [10], and it has been cited close to 600 times by now. Its publication gave me confidence that I was able to do my own research in the area dealing with the nonlinear effects in optical fibers.

I wrote my first book on semiconductor lasers during the year 1985, and it had appeared in print by the end of 1986 [7]. As a result, I was looking for a new book project. It occurred to me that no book had yet been written dealing with the nonlinear effects in optical fibers, and this topic might be ripe for a book. My initial working title for the new book project was "Pulse propagation in optical fibers". However, when I tried to make a table of contents, I realized that the book's scope was too narrow to be useful for the optics community. After a few days of planning, I changed the working title to "Nonlinear effects in optical fibers". Although this title was descriptive, I was not satisfied with it and kept thinking of a better one. I went to the library and noticed books with titles such as nonlinear optics and fiber optics. I also came across the term fiber nonlinear optics and a review paper of Roger Stolen

with the title nonlinearity in fiber transmission [11]. After some thinking, I decided to use the title *Nonlinear Fiber Optics* for my second book.

Before writing the book, I tried to make its table of contents. My objective was to arrange the chapter such that a reader, new to the field of nonlinear fiber optics, could learn it in a progressive manner. This forced me to start with the basic concepts such as group-velocity dispersion, the Kerr effect, and self-phase modulation and use them to introduce the topic of optical solitons. Such an approach also pushed the nonlinear effects involving two or more waves of different wavelengths toward the end of the book. This is the reason why the last three chapters in the first edition of *Nonlinear Fiber Optics* were devoted to stimulated Raman scattering, stimulated Brillouin scattering, and four-wave mixing.

I started writing the book in the summer of 1987. At the same time, I sent a book proposal to the Academic Press because I liked the books published by this company. The proposal was accepted, and I signed a contract with a delivery date in December 1988. I also asked my department at Bell Labs to allow me to spend 20% of my time on the book project. However, my request was denied, and I was asked to write the book in the evenings and over the weekends. Fortunately, Bell Labs' management permitted me to use internal resources for typing the manuscript and preparing figures for the book. Thus was crucial for me as drafting cost for each figure was nearly $100 in those days. It may appear surprising to most readers of this article, but I did not use a computer for writing the first edition of the book. Rather, I wrote each chapter by hand and took it to the typing division of Bell Labs. After the chapter was typed, I corrected errors by hand and resubmitted it. Multiple iterations were required for each chapter.

During the writing phase, I had to consult a large number of research articles published in the field of nonlinear fiber optics. I discovered that three groups were most active in this area. One of them was Roger Stolen's group at the Bell Labs location in Holmdel, New Jersey [12]. Stolen had started working in this area soon after low-loss fibers became available in 1970. His group's contributions covered different aspects of nonlinear fiber optics ranging from stimulated Raman scattering [13] to four-wave mixing [14] to spectral broadening induced by self-phase modulation [15]. The second group, led by E. M. Dianov at the Institute of General Physics in Moscow, Russia, also covered multiple aspects of nonlinear fiber optics in the 1980s [16–19]. The third group, led by J. R. Taylor at Imperial College, London, focused on short pulses acting as solitons and their compression [20–23].

Stolen teamed up with Linn Mollenauer and Jim Gordon around 1979, and their team made the first observation of solitons in optical fibers [6], predicted in 1973 by Hasegawa and Tappert [5]. Many other advances were made by this team during the 1980s, one of them being the discovery of the soliton's self-frequency shift through Raman scattering of short pulses in optical fibers [24].

4. Submission and publication of the book

In April 1988, I was offered a faculty position at the Institute of Optics of University of Rochester. I was interested in moving from industry to academia, and this appeared to be the best opportunity, given the reputation of the Institute of Optics. However, I was asked to join the faculty by September when the Fall semester began. This created a dilemma for me as I was in the middle of writing the *Nonlinear Fiber Optics* book and had to deliver the manuscript to the publisher by December 1988. Fortunately, University of Rochester agreed to my request to delay my appointment until January 1989.

I had to pass one more hurdle. Bell Labs's regulations required an internal review of the book's manuscript before it could be sent to its publisher. As this review took at least one month, I had to have the manuscript ready by October 15, 1988. Around that date, I submitted multiple bound copies of the entire manuscript to the Bell Labs's Book Review Board and waited patiently. Surprisingly, I was told after one month that my book would not be released for external publication because one reviewer had indicated it contained proprietary material. This was not the case, in my opinion, as I has used only the material that had already been published in technical journals.

As I did not have much time to waste, I went to see the Chair of the Book Review Board, who happened to be the well-known scientist, C. K. N. Patel, inventor of the carbon dioxide laser [25]. I told him that one reviewer's opinion should not be allowed to block my book project that I have worked on for more than a year and that he should seek other opinions in this matter. Luckily for me and the optics community, Dr. Patel was receptive to my argument. I suggested to him the names of Roger Stolen and Linn Mollenauer as the potential reviewers of my book. I had given earlier to both of them a copy of my manuscript asking for their suggestions. I am not sure if they were asked review my book, but the manuscript was released by the Board around December 10, 1988.

The last step was to submit a camera-ready copy of the book's manuscript. This process is now routine with the LaTeX software, which generates a PDF file for electronic submission. In 1988, the advent of the Internet was more than five years away. In fact, I had not even heard of such a thing as an email address. The only software that I had access to at Bell Labs was called "Troff", and the manuscript was prepared with it on a computer running the UNIX operating system. As the publisher was not setup to accept a magnetic tape, the only solution was to print the book in a camera-ready form with blank spaces left for figures. The publisher planned to paste figures in those spaces. I am sure modern readers will laugh learning about the use of such a technique for publishing the first edition of the *Nonlinear Fiber Optics* book.

Finding a laser printer with a resolution of 600 dots per inch (dpi) was not easy in 1988. The laser printers were relatively new at that time, and most of them had a resolution of only 300 dpi. After considerable search, I was able to locate one laser printer in the entire Bell Labs with the 600-dpi resolution. After some work, I got permission to use this printer. I printed the entire book using it and mailed the manuscript and all figures to the publisher around December 20, 1988. That was just in time because I moved to Rochester on December 23, where I had bought a house. A few days later, I started my new job as a faculty member of the Institute of Optics.

I should add that I was successful in bringing an electronic copy of the book's manuscript with me. Moreover, I was able to convert it to the LaTeX format in 1995, when I did the second edition of the *Nonlinear Fiber Optics* book. I also generated an improved version of most figures using the Matlab software. Although this process was time-consuming, it has allowed me to produce six different editions of the book without the help of a typist or a secretary.

I am grateful that the optics community has found the *Nonlinear Fiber Optics* book useful for research, as is apparent by its more than 30,000 citations since publication of the first edition (as per Google Scholar). The book has also trained a whole generation of young scientists in a technologically relevant research area. I find this later aspect especially gratifying. It is my sincere hope that the book will keep meeting the needs of the optics community.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

References

[1] G.P. Agrawal, Nonlinear Fiber Optics, 6th ed., Academic Press, 2019.
[2] R.J. Sanferrare, Terrestrial lightwave systems, AT T Tech. J. 66 (1987) 95–107, http://dx.doi.org/10.1002/j.1538-7305.1987.tb00478.x.
[3] G.P. Agrawal, Fiber-Optic Communication Systems, fifth ed., Wiley, 2021.
[4] The Nobel Prize website; https://www.nobelprize.org/prizes/physics/1977/anderson/facts/.
[5] A. Hasegawa, F. Tappert, Transmission of stationary nonlinear optical pulses in dispersive dielectric fibers. I. Anomalous dispersion, Appl. Phys. Lett. 23 (1973) 142–145.
[6] L.F. Mollenauer, R.H. Stolen, J.P. Gordon, Experimental observation of picosecond pulse narrowing and solitons in optical fibers, Phys. Rev. Lett. 45 (1980) 1095–1097.
[7] G.P. Agrawal, N.K. Dutta, Long-Wavelength Semiconductor Lasers, Van Nostrand Reinhold, 1986.
[8] M.J. Potasek, G.P. Agrawal, S.C. Pinault, Analytic and numerical study of pulse broadening in nonlinear dispersive optical fibers, J. Opt. Soc. Amer. B 4 (1986) 205–212.
[9] G.P. Agrawal, M.J. Potasek, Nonlinear pulse distortion in single-mode optical fibers at the zero-dispersion wavelength, Phys. Rev. A 33 (1986) 1765–1776.
[10] G.P. Agrawal, Modulation instability induced by cross-phase modulation, Phys. Rev. Lett. 59 (1987) 880–883.
[11] R.H. Stolen, Nonlinearity in fiber transmission, Proc. IEEE 68 (1980) 1232–1236.
[12] R.H. Stolen, The early years of fiber nonlinear optics, J. Lightwave Technol. 26 (2008) 1021–1031.
[13] R.H. Stolen, E.P. Ippen, A.R. Tynes, Raman oscillation in glass optical waveguide, Appl. Phys. Lett. 20 (1972) 62–64.
[14] R.H. Stolen, Phase-matched-stimulated four-photon mixing in silica-fiber waveguides, IEEE J. Quantum Electron QE-11 (1975) 100–103.
[15] R.H. Stolen, C. Lin, Self-phase-modulation in silica optical fibers, Phys. Rev. A 17 (1978) 1448–1453.
[16] E.M. Dianov, A.M. Prokhorov, V.N. Serkin, Soliton generation possibility in fibers of mid-IR region of light guides, Sov. Phys. Dokl. 28 (1983) 1036–1040.
[17] E.M. Dianov, A.Y. Karasik, P.V. Mamyshev, A.M. Prokhorov, V.N. Serkin, M.F. Stel'makh, A.A. Fomichev, Stimulated-Raman conversion of multisoliton pulses in quartz optical fibers, JETP Lett. 41 (1985) 294–297.
[18] A.B. Grudinin, E.M. Dianov, D.V. Korobkin, A.M. Prokhorov, V.N. Serkin, D.V. Khaidarov, Decay of femtosecond pulses in single-mode optical fibers, JETP Lett. 46 (1987) 221–225.
[19] E.M. Dianov, A.B. Grudinin, A.M. Prokhorov, V.N. Serkin, Non-linear transformation of laser radiation and generation of Raman solitons in optical fibers, in: J.R. Taylor (Ed.), Optical Solitons: Theory and Experiment, Cambridge University Press, 1992, Chapter 7.
[20] A.S. Gouveia-Neto, A.S.L. Gomes, J.R. Taylor, High-order soliton pulse compression and splitting at 1.32μm in a single-mode optical fiber, IEEE J. Quantum Electron QE-23 (1987) 1193–1198.
[21] A.S. Gouveia-Neto, A.S.L. Gomes, J.R. Taylor, A femtosecond soliton Raman ring laser, Electron Lett. 23 (1987) 537–538.
[22] A.S. Gouveia-Neto, A.S.L. Gomes, J.R. Taylor, Pulses of four optical cycles from an optimized optical/fibre grating pair/soliton pulse compressor, J. Modern Opt. 35 (1988) 7–10.
[23] J.R. Taylor, Soliton-Raman effects, in: J.R. Taylor (Ed.), Optical Solitons: Theory and Experiment, Cambridge University Press, 1992, Chapter 11.
[24] L.F. Mollenauer, J.P. Gordon, Solitons in Optical Fibers: Fundamental and Applications, Academic Press, 2006.
[25] C.K.N. Patel, Continuous-wave laser action on vibrational-rotational transitions of CO_2, Phys. Rev. 136 (1964) A1187–A1193.