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Editorial overview

Solitons and coherent structures in optics: 50th anniversary of the prediction of optical solitons in fiber

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ABSTRACT

Nonlinear optics is a continuously expanding field due to its wide range of applications covering temporal, spectral, polarization or spatial features of the light signals. 2023 was the celebration of 50 years since the numerical prediction of the existence of solitons in optical fiber by Hasegawa and Tappert and, to celebrate this milestone, Optics Communications invited submissions related to nonlinear coherent structures in optical waveguides involving the Kerr nonlinearity. The purpose of this Special Issue was to provide an overview of recent ongoing progress and trends in advancing the knowledge, understanding, and novel applications of optical solitons and other related nonlinear structures. Both theoretical and experimental reports or discussions were welcomed.

2023 was a year marked by the celebration of the 50th anniversary of the publication of the original articles written by Akira Hasegawa and Fred Tappert predicting the generation of temporal solitons in single mode optical fibers [1,2]. On this occasion, a Special Issue was launched by the Optics Communications journal to give an up-to-date overview of the latest research on nonlinear photonics in the field of optical fibers. With more than fifty contributions received, 38 of which were accepted for publication, this Special Issue shows that the nonlinear optics community remains extremely active. The significance of this golden jubilee was also highlighted by several dedicated special issues in other journals [3,4], in particular, one published in Optik, with an orientation towards more theoretical aspects. Review articles on the topic have also found an audience in the most renowned journals [5] or in publications aimed at the popular audience [6,7]. This anniversary also led to some special sessions in major conferences such as CLEO 2023 held in San Jose, California.

The concept of a soliton has its roots in the canal observations of the 'solitary wave' by John Scott Russell in 1834 [8], which were confirmed a few decades later by Henry Bazin in Burgundy [9]. At the end of the 19th century, Diederik Korteweg and Gustav de Vries as well as Joseph Boussinesq mathematically demonstrated the existence and the intrinsically nonlinear nature of these waves, which are capable of propagating over long distances without deformation. The progress in numerical experiments and the advent of powerful mathematical methods, such as the inverse scattering transform [10–12], made it possible to better understand the particle-like features of these waves, dubbed 'solitons' [13], the interest of which extends far beyond the initial field of hydrodynamics [14,15].

It was in this exciting context of the early 1970s [16] that Hasegawa and Tappert published their visionary 1973 articles proposing that the combination of Kerr nonlinearity and chromatic dispersion in silica could give rise to stationary picosecond waves able to propagate without change in a single-mode optical fiber [1,2]. Beyond their fundamental importance in nonlinear applied science, these inspiring articles (of only a few pages each) are also remarkable for containing the first statement of the nonlinear Schrödinger equation (NLSE) in the context of optical fibers. Another important aspect of these papers was Tappert's presentation of the split-step Fourier numerical scheme [17], an algorithm which remains the standard method for numerically solving the NLSE and its extensions even today. The experimental study of nonlinear effects in fibers was still in its infancy at that time and indeed, the first report on the Kerr nonlinearity in silica waveguides [18] by Roger Stolen and Arthur Ashkin also appeared in 1973. It is interesting to note that Ashkin, before his work on optical tweezers recognized by the 2018 Nobel Prize, exercised his talents in the field of nonlinear optics and demonstrated spatial solitons [19].

In this Special Issue, we have aimed to combine some important historical reflections with current and emerging developments. We are very grateful to Akira Hasegawa for inaugurating this Special Issue with thoughts and anecdotes about his research at Bell Labs and the discussion of some future prospects [20]. As Hasegawa acknowledges, the impact of his work owes a great debt to Linn Mollenauer and others at Bell Labs, who performed the first experiments on soliton propagation in fiber [21], as well as many other international groups who rapidly saw the potential of fiber solitons in communications and other areas of optics. Among these pioneers, Roy Taylor studied many aspects of solitons and related fiber propagation effects, and in this Special Issue, he looks back at this early work at Imperial College, including the exploration of ultrashort light sources, the advent of amplifiers and some of the first experiments on supercontinuum generation [22]. The challenges faced by the early-days soliton research were not only experimental but also theoretical, in particular raising questions about the

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existence of solitons in the presence of higher-order effects, or in the presence of birefringence or polarization mode dispersion, for which fully satisfactory models were not yet available. In this context, Curtis Menyuk's important contribution here in describes the development of the vector NLSE that addressed these issues [23]. Beyond these Special Issue's articles, other works also provide important historical context [24–26].

The Special Issue also includes 35 additional contributions that together illustrate the remarkable continued interest in the field of fiber solitons and related phenomena. This activity is also reflected in the bibliographic indicators and indeed, the Clarivate Web of Science database on the topics of "soliton" and "fiber" or "optical waveguide" returns no less than 18 000 contributions over the period 1980–2024, the distribution of which according to the publication year is summarized in Fig. 1. In other words, even 50 years after their proposal, more than a thousand contributions are now published annually related to the topic of fiber solitons, and this is a figure that is still growing. A further proof of the continued interest in this field lies in the number of citations of one of the seminal reference works in the field, the book *Nonlinear Fiber Optics* written by Govind P. Agrawal [27,28], which since 2005, has received more than 1000 citations per year. Optical solitons and nonlinear processes in fibers are by no means a challenge of the past but remain an object of intense study from both a fundamental and an applied standpoint.

Therefore, the bursting of the Internet bubble and the pause of optical telecommunications, which was the initial application foreseen for solitons, has been largely offset by new avenues of study, starting with the role of coherent structures in the generation of optical supercontinuum made possible by a new generation of fibers with engineered dispersion [26,29,30]. Indeed, a scientometric analysis carried out for the last decade (i.e., including nearly 8500 contributions) using the CiteSpace tool [31] reveals a predominance of two interconnected themes: (i) the subject of optical rogue waves initiated 15 years ago [32] accompanied by a renewal of interest in breathers and solitons on finite background [33]; and (ii) the subject of dissipative solitons, which has generalized the study of fiber solitons into systems with energy exchange, including lasers and other classes of resonators [34]. Very interesting to note is also the great geographical diversity of researchers in this field, which is also reflected in the contributions that we have had to this Special Issue, representing the 5 continents as shown in Fig. 2. We also see a very good balance between experimental and theoretical contributions, showing that the upstream aspects are just as exciting as the practical demonstrations of the most advanced concepts.

Solitons and associated dynamics retain an undeniable physical interest, especially thanks to the analogies that can be drawn with other branches of physics. Therefore, Vladimir N. Serkin, another major researcher present from the very early days of soliton research [35,36], develops with Tatyana L. Belyaeva a theoretical framework that establishes an extremely interesting analogy between well-dressed repulsive-core solitons and nuclear reactions [37]. Alexei M. Zheltikov, who has explored the opportunities of photonic crystal fibers for ultrashort light manipulation [38] amongst other things, sheds new light on the Lagrangian structure, the Euler equation, and Newton's second law that can be used to describe NLSE-governed nonlinear pulse propagation [39]. Using a recirculating loop system, François Copie, Pierre Suret and Stéphane Randoux provide an illustration of one of the most remarkable properties of solitons, i.e., their particle-like nature in a collision process [40]. Individual solitons may indeed collide, but a defining feature is that they pass through one another and emerge from the collision unaltered in shape, amplitude or velocity, but with a temporal shift whose value is impacted by the phase difference between the initial pulses. The soliton concept has been extended far beyond the case of the standard NLSE, and its existence has been demonstrated in non-isotropic fibers [23] as well as in the presence of higher-order dispersive effects. Martijn de Sterke, who has also thoroughly investigated Bragg grating solitons [41] and gap solitons [42] in the past, and Andrea Blanco-Redondo offer us a general view of these higher- and even-order solitons [43] that they have excited in waveguides [44]. Importantly, these solitary waves feature different scaling properties in terms of peak-power/duration compared to usual solitons, thus potentially paving the way to an increase of the pulse energy. Furthermore, in Ref. [45], Mojdeh S. Najafabadi and members of the group of Gerd Leuchs discuss the effects of the Kerr nonlinearity from a quantum point of view.

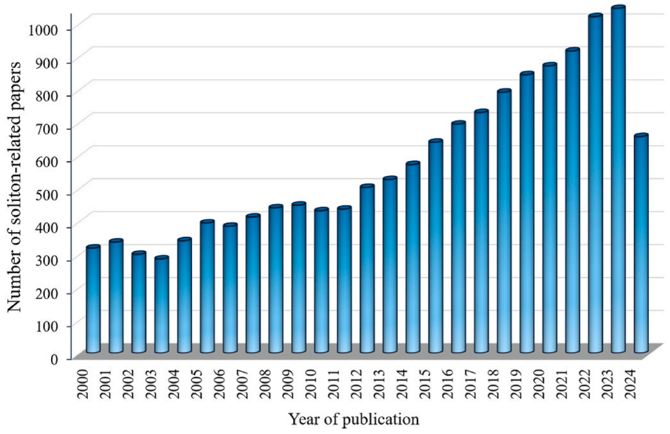

Fig. 1. Scientometric analysis showing the evolution of the number of soliton-related papers since 2000. The horizontal axis shows the year, and the vertical axis shows the number of articles indexed in the Web of Science database.

Whilst approaches to telecommunications system design based on ideal solitons have not been developed as originally envisaged, the role of nonlinearity in communications is a current topic of exciting research [20,46]. Two articles from German and Japanese groups, respectively, highlight the prospect and the challenges of encoding signals using eigen solutions of the NLSE through the inverse scattering transform method, also known as the nonlinear Fourier transform in the optics community [47,48]. More generally, the benefits brought by a different and powerful view of nonlinear dynamics are also discussed in the review of Yutian Wang and coworkers [49].

The spectral interactions involved in the nonlinear wave propagation in optical fibers have also been the subject of several contributions. These include the study of four-wave mixing and its idealized dynamics presented in the paper by Anastasiia Sheveleva et al. [50] and the closely related aspect of the observation of the Fermi-Pasta-Ulam-Tsingou recurrence [51,52] in a two-core optical fiber discussed by Jinhua H. Li et al. [53]. Frequency spectra with a comb structure have also been studied by Sonia Boscolo and coworkers, where the use of machine learning enables finding the conditions for optimal generation of custom profiles [54]. The application of machine learning techniques in ultrafast photonics significantly improves and expands the possibilities for the characterization and control of ultrafast propagation dynamics and the design of optical systems and devices with enhanced functionality [55]. Another closely related subject concerns the study of instability processes. Mehdi Mabed et al. discuss the ability of a neural network to reliably predict the peak intensity of the extreme events that are observed in fiber modulation instability [56], a key process tightly linked to soliton dynamics [22,57,58]. In Ref. [59], Bertrand Kibler and coworkers seek to avoid instabilities by using a normal-dispersion fiber pumped with femtosecond pulses to generate supercontinuum light in non-silica fiber.

Another aspect of the field that always stimulates research relates to advances in fiber design and nonlinear materials. In Ref. [59], it is the use of a dispersion-engineered chalcogenide glass fiber that paves the way for the extension of the supercontinuum beyond the absorption limits of silica glasses. This direction towards functional fiber solutions in the mid-infrared spectral region is currently hopeful and progressing rapidly [60]. The use of new media also brings about new questions. In

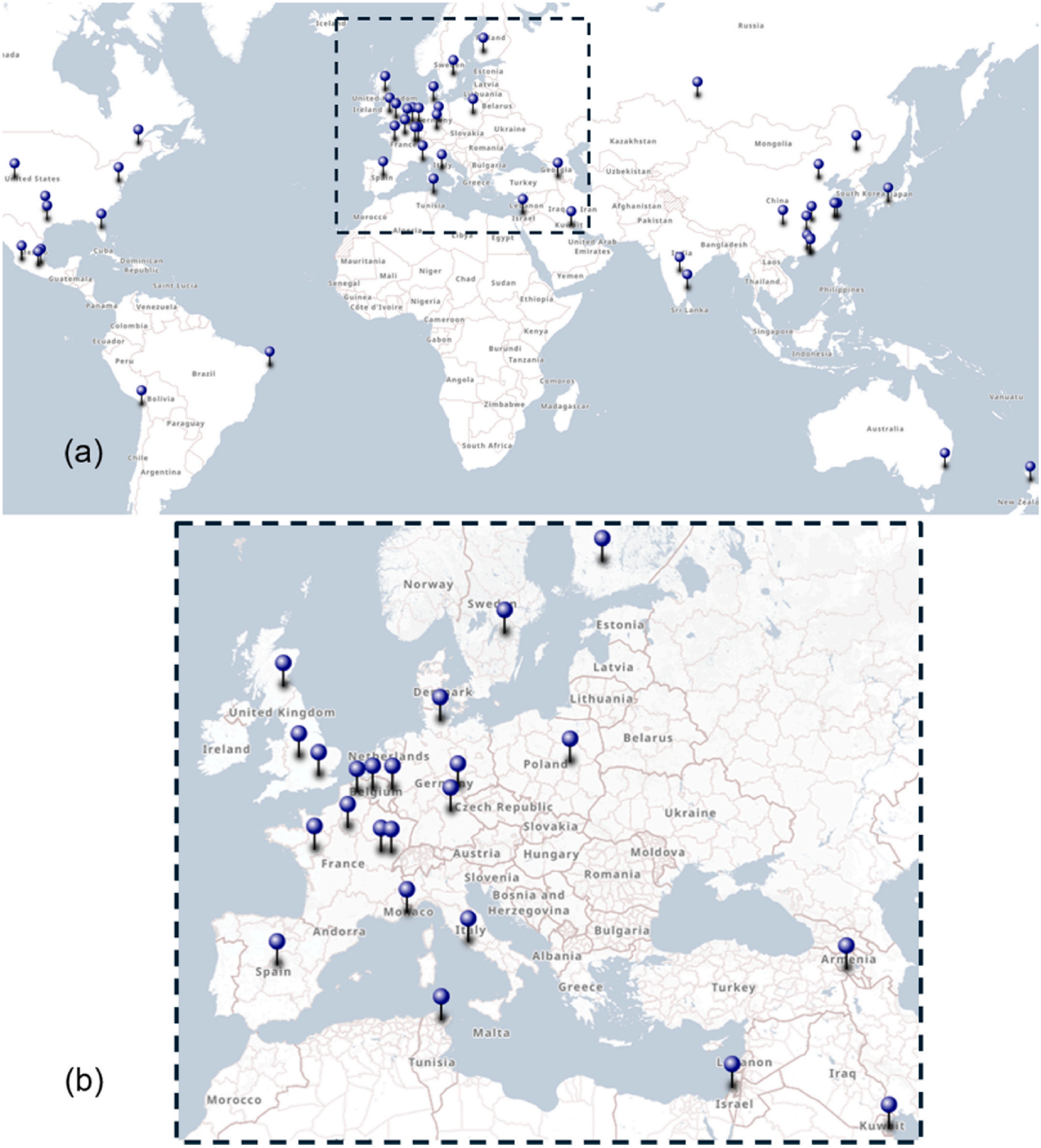

Fig. 2. Map representing the different contributors to this Special Issue. (a) World map and (b) zoom on European countries.

Ref. [61], John Travers provides a detailed and very important review of the challenges in the field of gas-filled hollow fibers, where the effect of plasmas must be accounted for in the process of solitonic compression. He also looks back to the progress made over two decades on solitons in hollow-core waveguides from the already impressive results of 2003 [62] to the astonishing performances reached in his group [63]. The gas pressure is one of the parameters that can enable remarkable levels of compression and reaching the sub-femtosecond regime with a high peak power. Pritha Dey and colleagues discuss this process in a numerical study by adopting an effective definition of the soliton order [64]. As an alternative to gases and aiming at different applications, fiber cores can also be infiltrated with liquid, which then results in a delayed nonlinear response enabling the adjustment of the usual soliton properties, as reported and explained by Mario Chemnitz in Ref. [65]. In their theoretical contribution [66], André C. A. Siqueira et al. study the benefits of using an alternation of fibers where the nonlinearity coefficient changes in sign thanks to the presence of nanoparticles, thereby enabling the generation of a train of compressed solitons.

If fiber solitons, as initially described by Tappert and Hasegawa, have been studied in the context of single-mode propagation, multimode and multi-core fibers have recently emerged as an exciting area of research, bringing in the associated issues of nonlinear spatial coupling. In Ref. [67], Alejandro B. Aceves shares some perspectives and new trends on discrete solitons in nonlinear waveguides arrays [68,69]. In Ref. [70], Antonio Picozzi, who has been one of the drivers of the progress of the statistical thermodynamic approach for nonlinear fiber optics [71], and coworkers theoretically and experimentally discuss the differences between Rayleigh-Jeans thermalization and beam self-cleaning in a multimode fiber with index gradient. In Ref. [72], Pedro Parra-Rivas, Yifan Sun and Stefan Wabnitz theoretically study the spatio-temporal properties of solitons in multimode waveguides. Indeed, following Hasegawa's early intuition [73], temporal and spatial confinement of light can be achieved in multimode fibers when some requirements are met.

The articles cited above are mainly concerned with single-pass propagation of pulsed or continuous-wave signals. Yet, a subject that has greatly continued to progress in recent decades is the study of solitons in optical cavities and laser oscillators in the presence of loss and/or gain. There are 12 contributions that study these dissipative or cavity solitons [34,74–84]. In his review [34,85], Philippe Grelu discusses the emergence of the dissipative soliton concept and the physical richness that it brings about, opening up a plethora of dynamics that are not observable with conventional solitons [34,85]. François Sanchez, Andrey Komarov and Georges Semaan provide an overview of the process of dissipative soliton resonance, leading to square-wave pulses with a constant peak power and increased pulse energy and duration [74]. Furthermore, a related area that has been actively researched is the development of saturable absorbers for laser mode locking. Haiqin Deng and colleagues provide a bibliographic review based on a scientometric approach of the latest developments in this field, particularly around low-dimensional materials in different emission spectral bands [75]. Physical saturable absorbers can also be emulated by artificial saturable devices such as the nonlinear optical loop mirror [76], figure-of-nine laser architecture [77] or nonlinear polarization rotation [78]. Experimental studies on mode-locked lasers have greatly benefited from the progress of ultrashort event analysis, in particular the time-stretch dispersive Fourier transform technique [86–88], which makes it possible to capture transient state-behavior in Refs. [32,76,89]. Numerical modeling also remains an important tool to predict the rich short-pulse dynamics that are supported by mode-locked lasers and/or understand the experimentally observed dynamics [77–79]. These dynamics go far beyond stationary single solitons, by encompassing soliton pairs or molecules [84], and breathing dissipative soliton (or pulsating soliton) states [76,77] that feature a universal fractal dynamical behavior [78,90]. Here again, machine-learning techniques open up new possibilities for this computationally demanding task [79]. Control of the intracavity dispersion [91] enables the observation of quartic solitons as well as a numerical study of the impact of saturable absorption in Ref. [80]. Going beyond these works on laser fiber cavities, Pedro Parra-Rivas presents a variational formalism for dissipative solitons in a singly resonant parametric oscillator in Ref. [92]. It is worth to note that an optical cavity does not necessarily require gain to show new physical behaviors [93,94]. Therefore, Julien Fatome and coworkers discuss the temporal manipulation of a different family of solitons, the domain-wall solitons, in a nonlinear Kerr cavity [81], while Francesco Rinaldo Talenti and coworkers demonstrate that the pulse chirp enables control and stabilization of cavity solitons and breathers [82]. Coupling effects represent an additional degree of freedom, whether they are coupling between two mode-locked synchronized cavities as demonstrated by Zhenrui Li in Ref. [83] or intra-cavity coupling between two states of light. Gang Xu et al. present a review of these processes [84].

Finally, we would like to mention two contributions dedicated to the memory of other two pioneers of the field, who made significant impact on the community. These are tributes to the late Kuppuswamy Porsezian (1963–2018) who influenced the theoretical developments of soliton research in India in many ways [95], and Levon Mouradian (1956–2018) who initiated the nonlinear optics activity at the University of Yerevan in Armenia with remarkable results in the field of ultrafast pulse characterization and temporal and spectral nonlinear processing [96]. In this regard, we also wish to acknowledge here the great pioneer of soliton physics and nonlinear wave theory, Vladimir Zakharov (1939–2023), whose research cuts across multiple disciplines, and who played a major role in creating an international community of researchers in the field [11,97].

In closing, we express the hope that the reader will have the same pleasure as we did in reading these 38 contributions from more than 125 authors representing nearly 50 different research centers, and which have led to a collection exceeding 350 printed pages. This collection has naturally found its place in Optics Communications, which has welcomed the subject of solitons since the 1980s [93,98–107]. Indeed, amongst the 18000 bibliographic references between 1980 and 2024, more than 700 were published in this journal, thus positioning it in the fourth place among the journals with the most articles on solitons in optical fibers, behind Optics Express, Optics Letters and Optik.

We are confident that the reader will agree with us that the study of optical solitons remains an extremely active field, with results regularly appearing in the very best and most selective journals. We would therefore like to warmly thank all the contributors, and we add a special appreciation to the authors who prepared articles with a more personal perspective or who addressed topics in the field from a new angle. We can now look forward to even more exciting research and perhaps a comparable collection of papers on the fiber soliton's 75th anniversary where we can anticipate a new generation of researchers taking the lead.

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.

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