Optical soliton: Review of its discovery and applications in ultra-high-speed communications

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This paper reviews the discovery of the optical soliton and historical attempts of its applications in ultra-high-speed communications. It also reveals various episodes that took place in the course of its discovery and in subsequent developments in the form of a memoir. The paper is expected to stimulate young scientists for their future activities and contributions.

KEYWORDS

optical soliton, soliton control, dispersion-managed soliton, soliton eigenvalue communications, soliton

1 Introduction

It is my great pleasure to write a memoir on the discovery and applications of the optical soliton in the dielectric fiber at the time of its 50th anniversary of its discovery. The original paper that was published in Applied Physics Letters in 1973 is still widely cited, and the citation number had exceeded over 2000 and is still increasing. The manuscript is intended to be a memoir on the incident, rather than an original work.

I was an Associate Professor at Osaka University till 1969 when I moved to the Murray Hill branch of Bell Laboratories. One phenomenon that attracted me at the time was the nonlinear effects of the electron cyclotron wave called "whistler," often observed in space and on the ground. Professor T. Taniuti at Nagoya University, who was my mentor on nonlinear waves, published with his students a paper on modulation instability of the whistler. This is a new type of plasma instability in which it is essentially nonlinear, and the growth rate depends on the wave power. The instability is generally describable by the nonlinear Schrödinger equation, where the potential term depends on the magnitude squared of the wave amplitude. A similar equation was also used previously to demonstrate self-focusing of the light wave in nonlinear dielectric media, if the group dispersion is replaced by the refraction. The equation has a stationary localized solution, which is later called an envelope soliton in contrast to a conventional soliton where the wave amplitude itself becomes a soliton. The importance of a soliton is its integrability, that is, the nonlinear equation is integrable given the initial local perturbations, and the solution can be described by a set of solitons and linear dispersive waves. In this regard, solitons are also called nonlinear Fourier modes.

Meanwhile, at Bell Laboratories, studies on light-wave communications by means of dielectric fibers began in the early 1970s. It was immediately recognized that the fiber group dispersion distorts the information carried by the light wave in fibers. The group dispersion is the dispersion of the group velocity that is caused by its dependence on the wave numbers. I noticed that the glass fiber has cubic nonlinearity whereby the index of refraction increases in proportional to the light intensity, i.e., the square magnitude of the light wave. This is called the Kerr effect, which is named after its discoverer. It did not take much time for me to derive the light wave envelope equation of the glass fiber that includes the Kerr nonlinearity and the group dispersion in the form of the nonlinear Schrödinger equation. The equation generally describes information transfer in optical fibers that is essentially nonlinear and dispersive. Knowing the fact that the equation has localized a solution, the optical soliton, I proposed to use the solution for optical communications and published the concept in Applied Physics Letters with a coauthor, Fred Tappert, who performed various computer simulations to demonstrate the stability of the soliton [1, 2]. Here, bright solitons appear in an anomalous dispersion regime, while dark solitons appear in a normal dispersion regime. Meanwhile, the nonlinear Schrödinger equation that describes the self-focusing was successfully solved by Zakharov and Shabat [3], and the solution is in fact given by a set of solitons (envelope soliton) and dispersive waves. We were not aware of this paper as it was published originally in Russian; thus, Fred performed various numerical simulations to demonstrate the stability of the optical soliton. The papers by Hasegawa and Tappert [1, 2] are now regarded as the original work of optical solitons, whose 50th anniversary is commemorated by this special issue. Here, it may be worth disclosing the fact that Norman Zabusky, who was the boss of Fred Tappert at the Whippany branch of Bell Laboratories and the co-inventor of the term soliton, rejected the paper to be sent to Physical Review Letters in the internal review. This made me to send the paper to Applied Physics Letters instead. It is ironical that an inventor of the name soliton, Norman, did not like the first paper on the optical soliton.

2 Review of soliton concept, discovery of the optical soliton, and its application in ultra-high-speed communications

2.1 Historical background and discovery of the optical soliton

A soliton was first observed by Russell [4] as a water surface wave in 1844. Korteweg and de Vries in 1895 [5] derived (known as the K-dV equation) a model equation that describes a far field property of the water surface wave in the lowest order of dispersion and nonlinearity. When Zabusky and Kruskal

solved the equation numerically in 1965 [6], a set of solitary waves was found to emerge and stably pass each other. They named these solitary waves as solitons because of their stability. The term "soliton" was later justified theoretically when the K-dV equation was solved analytically by means of the inverse scattering transform (IST), and the solution was described by a set of solitons and dispersive waves [7]. Solitons are now regarded as a fundamental unit of a mode in a nonlinear dispersive medium and play a role similar to the Fourier mode in a linear medium. In particular, a soliton being identified as an eigenvalue in the IST supports its particle (fermion) concept. Meanwhile, self-focusing in a Kerr medium [8] was demonstrated, and a spatially localized solution analogous to a soliton was found to emerge by the balance of the cubic nonlinearity and refraction. The model equation, the nonlinear Schrödinger equation, was later found to be integrable by Zakarov and Shabat [3] also by means of the inverse scattering transform, and the solution is given by a set of solitons and dispersive waves. The model equation derived by Hasegawa and Tappert for the light wave transmission in fibers also has the structure of the nonlinear Schrödinger equation, where the refraction is replaced by the group dispersion; hence, an optical pulse in fibers emerges as a set of optical solitons and dispersive waves as it propagates.

2.2 Discovery of the optical soliton

The first experimental demonstration of the existence of a (bright) optical soliton was performed by Lynn Mollenauer et al at the Holmdel Branch of Bell Laboratories in 1980 [9]. However, few people expected the importance of solitons in practical use because there was erroneous belief that anything "nonlinear" would be too complicated and take enormous power. As a matter of fact, Arno Penzias, the President of Bell Laboratories and the Nobel Laureate for the discovery of the universe background radiation, once visited Mollenauer's laboratory and discouraged him in continuing the work. Lynn defied Arno's suggestion and continued the experiment. When Mollenauer later succeeded demonstrating the long distance transmission of solitons in fibers [10], Arno admitted his mistake and made an apology at the New Year's speech to the laboratory members saying that laboratory management should not interfere in the direction of scientist's free research studies. This incident has led to the first page article in the Wall Street Journal published on 25 June 1991 entitled Defying Boss's Orders Pays Off for Physicist and His Firm, AT&T. The misjudgment made by Arno is understandable since the Kerr nonlinearity of glass is so tiny, i.e., $10-22$ $(m/V)^2$, and the nonlinear effect is seemingly quite insignificant. However, since this tiny change in the dielectric constant occurs at every light wavelength (~$10-6$ m) of the pulse propagation, the integrated nonlinear effects over several thousand kilometers of

propagation can become significant even at a few milliwatts of light wave intensity.

2.3 Idea and demonstration of all-optical soliton transmission system

Since solitons do not suffer distortion from nonlinearity and dispersion that are inherent in fibers, the natural next step was to construct an all-optical transmission system in which fiber loss is compensated by amplifications [11]. The long distance optical communication had required periodic repeaters that reshape the optical signal, which had been the bottleneck of linear transmission systems. In the absence of a realistic optical amplifier at that time, I proposed to use the Raman gain of the fiber itself [12]. The idea was used in the first long-distance all-optical transmission experiment by Mollenauer and Smith in 1988 [10]. Lynn at the presentation of the work commented "I thought the Akira's idea of using the optical soliton for a high-speed communication was crazy but that of using Raman amplification was even crazier but they all worked." This experimental result has ignited serious interests in optical communication society. In particular, the invention of erbium-doped fiber amplifiers (EDFAs) has elevated the concept of all-optical transmission system to a more realistic level as initiated by Nakazawa et al [13] in the first reshaping experiment of optical solitons. In this case, however, the pulse shape at an arbitrary position along the fiber deviates from a soliton. Hasegawa and Kodama, using the Lie transformation, have succeeded in 1990 [14] by demonstrating that the properly transformed amplitude does satisfy the ideal nonlinear Schrodinger equation to the order $(za/z0)^2$, where za and z0 are the amplifier spacing and dispersion distance, respectively, and are called the transformed amplitude "guiding center soliton." The guiding center soliton warrants the integrability of the periodically amplified soliton transmission system.

2.4 Identification of possible problems

The concept of all optical soliton transmission by periodic amplifications has been challenged by several authors. Gordon and Haus [15] predicted that the amplifier noise would induce frequency modulation and result in time jitter in the soliton position. Dianov et al [16] predicted that side scattering of phonons would also induce time jitter. Chu and Desem [17], Blow and Dran [18], and Hermansson and Yevick [19] have published papers on the effects of interactions between neighboring solitons. Although the single-mode fiber was found needed in the early stage of the pulse transmission, two orthogonal polarizations of the single mode possess the polarization-mode dispersion and induces splitting of a pulse.

It was shown, however, that if the polarization shifts randomly within a distance much shorter than the dispersion distance, this effect may be averaged out, and the ideal nonlinear Schrödinger equation can be recovered [19]. Collisions between solitons in different channels in soliton WDM systems [20, 21] in the input [22] as well as in amplifiers [21] have been predicted to cause time-position shifts. Higher-order terms in linear and nonlinear dispersion were expected to deform solitons and shift soliton velocities [23]. Higher-order nonlinear dissipation (self-induced Raman effect) was found to decelerate solitons [24, 25]. Attempts to solve these problems have ever since been made, and significant progress has been achieved.

2.5 Demonstration of soliton control

Most of the problems stated in Section 2.4 can either be reduced or solved by means of soliton control or by dispersion management. The soliton control is based on the robust property of solitons. Thus, the control of soliton characteristics, such as amplitude or width, time position, velocity or frequency, and phase is sufficient. This means, while the original wave equation has an infinite dimension, control of finite dimensional parameters is sufficient in controlling the soliton transmission systems. This fact presents an important merit of a soliton system. Control of solitons may be classified into passive and active means. Frequency filters inserted periodically in the transmission systems were found to be effective in reducing soliton time jitter [26, 27]. The idea of the use of the frequency filter came out independently by Herman Haus and his group and me and Kodama. Although these papers were published in different years, our paper [27] was received earlier than theirs [26]. The idea was further refined by Mollenauer et al, who succeeded in eliminating linear wave growth produced by the excess gain at the center frequency of the filter by sliding the filter frequency along the transmission [28]. The sliding frequency filters have enabled a record-breaking long-distance 20-gigabit signal transmission. The soliton parameters were found to be controlled also by active means. Nakazawa et al have demonstrated that practically unlimited distance of propagation can be achieved by a combination of temporal gain modulations and filters [29]. White Smith et al [30] as well as Wabnitz [31] have demonstrated the effectiveness of phase modulation control. Active control was also shown to be possible by means of injection of light waves to the fiber by Grigoryan et al [32].

2.6 Discovery of dispersion-managed optical solitons

In the early 1990s, by properly programming the fiber group dispersion in the direction of propagation, optical solitons with

significantly better quality have been discovered. The dispersion-managed solitons have properties with reduced Gordon–Hause jitter, reduced interaction between adjacent pulses, and reduced interaction among pulses in different WDM channels. Adiabatic (programming dispersion in proportion to the peak power) [33–35], nonadiabatic [36–40], and the mixture of these [41] are considered. Dispersion-managed soliton systems are most attractive for practical implementation of soliton systems.

2.7 Soliton eigenvalue communications

In a long-distance inter-continental communications, thermal efficiency is a crucial issue to save huge power required in repeaters. Solitons are known to preserve the eigenvalues in the inverse scattering transform, and thus information carried by them can be used as robust signals. If several eigenvalues and their combinations are used in a soliton as an information carrier, the information carried by a soliton increases significantly without increasing the repeater power. Based on the concept, Hasegawa and his student, Nyu, proposed soliton eigenvalue communication in 1993 [42]. The use of embedded multiple eigenvalues and its feasibility for communications in cross-phase modulation-induced higher-order soliton fission was demonstrated in 2004 [43]. To avoid receiver complications in the receiver configuration, an eigenvalue-modulated optical fiber transmission system based on digital coherent technology [44] was proposed in 2013 [45]. Almost at the same time, several IST (frequently referred to as nonlinear Fourier transform (NFT))-based modulation techniques were also proposed [46, 47]. Over the last decade, many studies were performed on the use of advanced modulation and transmission techniques based on eigenvalue communications. In 2020, machine learning-based demodulation methods for eigenvalue modulation were introduced, and significantly better performances are reported [48, 49]. In particular, Turitsyn et al. presented a nice review of the optical communication based on NFT in this regard [50].

3 Concluding remarks

My appreciation should be extended to Professor Akihiro Maruta for his contribution to Section 2.7 and his extensive review of the article. I would like to express my gratitude to Professor Qi Guo, who invited me to write this memoir. The gratitude should also be extended to a large number of scientists who showed interests in the subjects related to optical solitons during the past 50 years and perhaps years to come.

In conclusion of the review, I must admit and regret the fact that optical solitons are not used in the present-day high-speed communications in spite of the fact that soliton-based communications came very close to practical use in the early 1990s by KDD Japan. The main reason is that new fibers with a much larger cross section, which bundle a large number of individual single-mode fibers, were developed; therefore, the nonlinear effect is much reduced, and at the same time transmission capacity is increased, for example, by means of wavelength multiplexing (WDM). The linear transmission group won through the technical development of new fibers. While soliton groups are interested in physics of soliton transmission, they are not particularly concerned with the increase in the transmission rate, which is regarded as a technical problem. For example, since solitons at different wavelength channels pass through each other and hence much more suited for WDM transmission even with existing fibers, few people have paid much attention to it.

Author contributions

The author confirms sole responsibility for the following: study conception and design, data collection, analysis and interpretation of results, and manuscript preparation.

Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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