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A Historical Narrative of Study of Fiber Grating Solitons

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Abstract: A brief historical narrative of the study of grating solitons in fiber Bragg grating is presented from the late 1970's up to now. The formation of photogeneration gratings in optical fiber by sustained exposure of the core to the interference pattern produced by oppositely propagating modes of argon-ion laser radiation was first reported in 1978. One important nonlinear application of fiber Bragg grating is grating solitons, including gap soliton and Bragg soliton. This paper summarily introduces the numerous theoretical and experimental results on this field, each indicating the potential these solitons have in all-optical switching, pulse compression, limiting, and logic operations, and especially important for the optical communication systems.

Keywords: nonlinear optics, periodic structure, fiber Bragg grating, kerr nonlinearity, dispersion, grating solitons, Bragg soliton, gap soliton

1. Introduction

After the invention of the laser, there has been much interest in propagating nonlinear pulses through the periodic medium such as a fiber Bragg grating (FBG), which is a periodic variation of the refractive index of the fiber core along the length of the fiber. Since the first demonstration of photo-induced optical fiber Bragg gratings by Hill and coworkers in 1978 [1], significant progress was made in the fabrication technology of fiber Bragg reflectors [2–5]. The concept of "photonic band structure" is introduced by Yablonovitch in the late 1980's [6]. A notable feature of this linear periodic structure is the presence of stop gap in the dispersion curve popularly known as photonic band gap (PBG) [7,8]. This PBG exists at frequencies for which the medium turns highly reflective and hence the light pulse will not be able to propagate through the periodic structure. Light interaction with nonlinear periodic media yields a diversity of fascinating phenomena, among which two solitonic phenomena have been studied most intensively, namely, discrete (or lattice) solitons [9–11] and gap (or Bragg) solitons [12–17]. While discrete solitons are spatial phenomena in two-dimensional or three-dimensional arrays of coupled waveguides, gap solitons are usually considered as a temporal phenomenon in one-dimensional (1D) periodic media [18–20]. Perhaps the most fascinating feature of solitons is their particle like behavior. Survival of two such colliding solitons is even more remarkable if one notes that solitons interact strongly with each other during the collision. But for copropagating solitons, the interaction is either attractive or repulsive, depending on the relative phase between two solitons. In both cases the evolution of the soliton pair is well understood [21–24].

As first pointed out by Winful [25], because the dispersion is many orders of magnitude larger than the total dispersion due to the combined effects of material and waveguide dispersions that arise in the conventional fibers, the interactions lengths are reduced accordingly. Hence, the grating induced dispersion dominates over the total dispersion in the conventional fibers. When the entire spectral components of the input pulse lie within the PBG structure, the grating induced dispersion counterbalanced by the Kerr nonlinearity through the self-phase modulation (SPM) and cross-phase modulation (XPM) effects, forming solitons are referred to as gap solitons since their spectral components are within the PBG structure. Many research groups [3–10] theoretically predicted the existence of gap solitons and Bragg grating solitons in FBG and the investigations on these exciting entities are going on. However, it can be noticed that, in literatures, nowadays the distinction between gap solitons and Bragg solitons is hardly maintained and, in general, they are simply called grating solitons [26]. Ul [25], because the dispersion is many orders of magnitude larger than the total dispersion due to the combined effects of material and waveguide dispersions that arise in the conventional fibers, the interactions lengths are reduced accordingly. Hence, the grating induced dispersion dominates over the total dispersion in the conventional fibers. When the entire spectral components of the input pulse lie within the PBG structure, the grating induced dispersion counterbalanced by the Kerr nonlinearity through the self-phase modulation (SPM) and cross-phase modulation (XPM) effects, forming solitons are referred to as gap solitons since their spectral components are within the PBG structure. Many research groups [3–10] theoretically predicted the existence of gap solitons and Bragg grating solitons in FBG and the investigations on these exciting entities are going on. However, it can be noticed that, in literatures, nowadays the distinction between gap solitons and Bragg solitons is hardly maintained and, in general, they are simply called grating solitons [26].

2. Theory

The usual quantitative description of grating solitons employs coupled-mode theory, leading to the nonlinear coupled-mode equations. In addition, in the appropriate limit, the envelope of the electric field satisfies the nonlinear Schrödinger (NLS) equation. The pulse propagation through the FBG is described by the nonlinear-coupled mode (NLCM) equations which are nonintegrable in general. Therefore, the analytical solutions of the NLCM equations are not solitons but solitary waves that can propagate through FBG without changing their shape. These are obtained from the approximated nonlinear Schrödinger (NLS) equation that results from reducing the NLCM equations using the multiple scale analysis. The relation between the NLSE and the more general CME description, which was discussed earlier [28], is important. Gap solitons are obtained from the NLCM equations and their spectra lie within the photonic bandgap structure. There is another class of solitons called Bragg solitons obtained from the NLS equations whose frequencies fall close to, but outside, the band edge of the photonic bandgap. Generally speaking, the gap solitons are the special class of Bragg solitons.

For the first time, Chen and Mills [12] have analyzed the properties of these gap solitons in nonlinear periodic structure. Thereafter, Sipe and Winful published analyses showing that these “gap-solitons” are not only fundamental solutions in the weak-field regime but could be detected as propagating solutions in structures of finite length [14]. The general gap soliton solutions to the coupled mode equations were first obtained in a limiting case by Christodoulides and Joseph [16]. The solutions were first reported in their most general form by Aceves and Wabnitz [17]. Aceves and Wabnitz appoint parameters to form gap solitons in fiber Bragg grating, and the unique dispersion relation of the fiber grating, and the corresponding solitons, allows in theory all velocities from zero to the speed of light in the bare fiber. Their starting point is the massive Thirring model(MTM), and quantitative description of gap solitons employs coupled-mode theory, leading to the nonlinear coupled-mode equations [16,17]. At same time, Sipe and de Sterke examined, in further publications [27–29], the pulse transmission behavior as a function of both pulse energy and detuning from the Bragg resonance. Among the contributions of de Sterke, Sipe and others was a rigorous development of coupled-wave and multiple-scales approximations as well as the description of numerical methods [30] suitable for examining the regimes of instability of these structures. In a word, Sipe and Winful [14], Christodoulides and Joseph [16], Aceves and Wabnitz [17], and Winful *et al.* [31] have obtained the analytical solutions for the grating solitons. These solitons in FBGs have been extensively reviewed in [19,32]. Comprehensive analyses of Bragg solitons stability have also been reported [33,34]. Still other generalizations have been discussed by Feng and Kneubuhl [35] and by Feng [36]. In order to better simulate experimental conditions, Broderick, de Sterke and Jackson presented a method of numerically modeling periodic structures having optical nonlinearities [37]. Other important extensions and generalizations include a series of papers by Aceves and coworkers extending many of these principles to waveguide arrays [38].

Inverse scattering transform (IST) is currently the standard analytical technique for obtaining the soliton solution for the homogenous NLSE [39,40]. IST has been used to solve the two-dimensional space-time NLSE with initial-boundary conditions and coupled NLSE in the form of fundamental and higher-order solitons [39]. To our knowledge, no other analytical method has been published besides the IST for solving the NLSE systems. Another method can be described as effective particle pictures EPP’s, since they represent the continuous field distribution as a point particle with a limited number of degrees of freedom. The key difference between the NLSE and NLCME’s is that the NLSE is integrable, whereas NLCME’s are not [37], hence that an EPP would be more accurate in that case [42–46]. However, previously, gap soliton propagation in the presence of uniform gain and loss was succesfully treated using an EPP [43,47] method, which was also used by Capobianco et al. to treat propagation between two quadratically nonlinear materials [48]. One method to analyze deep gratings is using Bloch wave solutions as the fundamental waves. Actually the modulation of a single Bloch wave is known to obey the nonlinear Schrödinger equation in Kerr optical media [13,49,50], and its fundamental soliton corresponds to gap solitons in this geometry. Note that the Bloch function formalism has the feature that the linear system needs to be solved first, and the nonlinearity is then considered as a perturbation which can be treated in a variety of approximations. A different formalism developed for linear gratings only to treat deep gratings was reported by Sipe *et al.* [51]. The linear properties are therefore not obtained exactly, but in terms of an asymptotic series, only a few terms of which are retained. Nonetheless, the method leads naturally to low-order corrections to the coupled mode equations for shallow gratings. Then, one may expect that the model may give rise to two qualitatively different families of gap solitons: low-frequency ones, in which the self-focusing (cubic) nonlinearity is balanced by the dispersion branch with a sign corresponding to anomalous dispersion, and high-power solitons, supported by the balance between self- defocusing (quintic) nonlinearity and the normal branch of the dispersion. The simplest model of this type may be based on the cubic-quintic (CQ) nonlinearity that has recently attracted considerable attention, as the combination of the SF cubic and SDF quintic terms prevents collapse and makes it possible to anticipate the existence of stable solitons [52–60]. Atai and Malomed introduced the quintic nonlinearity into the NLCM equations and investigated two different families of zero-velocity solitons. One family was the usual Bragg grating solitons supported by the cubic nonlinearity. The other family was named as twotier solitons supported by the quintic nonlinearity [26]. In fact, in the cubic model, the final soliton retains only 11.6% of the initial energy, while the energy-retention share in the cubic-quintic model is 92.4% [59].

3. Experimentation and Applications

Recently conducted experiments have provided strong evidence for the existence of the grating solitons in FBGs [61–66]. To our knowledge, it was Larochelle, Hihino, Mizrahi and Stegeman [67] who were the first to report (in 1990) an experimental investigation of the optical response of nonlinear periodic structures. They employed an optical Kerr-effect cross-phase modulation in fiber gratings to achieve switching of a probe beam by a control beam.The first detailed experimental observation of all-optical switching dynamics in a nonlinear periodic structure was reported by Sankey, Prelewitz and Brown in 1992 [68]. Experimental observations of nonlinear grating behaviour are limited, principally by the difficulty in getting sufficiently high power densities within the core of a FBG in a suitable spectral and temporal range. In order to reduce the nonlinear threshold for gap soliton formation one can use the somewhat weaker dispersive properties of FBGs outside of the band gap. An investigation of nonlinear pulse propagation in uniform fiber gratings was published by Eggleton *et al.* in 1996 [61].In this report, the Bragg solitons are most easily generated in the laboratory travel at 60–80% of veocity of light in fiber absence of grating [61,64]. This was followed by further reports from the same group, which both refined the experimental technique and broadened the experimental understanding of the dynamics of pulse propagation in periodic structures [65]. In their initial experimental observations of Bragg solitons [61,62,64], the agreement between the experiments and the numerical calculations was qualitative. However, stationary (or nearly stationary) gap solitons have not been observed yet. Subsequently, the Southhampton group [69] first demonstrated switching at the important optical communication wavelength of 1550 nm, and in doing so have confirmed certain key aspects of the physics of pulse propagation in nonlinear periodic structures. We now understand that a Bragg soliton need not be centered near the Bragg resonance--indeed, some very interesting propagation effects occur rather far from the band edge. Experimental studies of BG solitons were further developed including, in particular, formation of multiple BG solitons inRefs [42]. Broderick et al. also report the first experimental demonstration of a novel type of all-optical pulse compression [71]. It is significant experimentation that Taverner *et al.* [42,70] reported the first observation of gap soliton generation in a Bragg grating at frequencies within the photonic bandgap. Furthermore the sets of experiments were performed in relatively short gratings. Thus, in these experiments, pure soliton propagation effects are difficult to distinguish from effects due to soliton formation. The occurrence of modulational instability (MI) in fibers had been first suggested by Hasegawa and Brickman [72] and experimentally verified by Tai *et al.* [73]. The effects of MI which occurs when a perturbed continuous wave experiences an instability that leads to an exponential growth of its amplitude or phase during the course of propagation in optical fibers due to an interplay between the nonlinearity and group velocity dispersion (GVD) act in opposition. THE studies on modulational instability (MI) have some impacts on solitons [8,74,75].

The researchers recently have realized the potential applications of these solitons in fiber Bragg grating for all-optical switching [67,76,77], pulse compression [69,71,78], limiting [80], and logic operations [81,84], also promising for the fiber-sensing technology [79], especially important for the optical communication systems [78,82]. One would hope to achieve zero velocity by a clever tailoring of the Bragg grating. This research goes beyond its intellectual value; all optical buffers and storing devices can be based on such fibers. About logic operations, for the first time to our knowledge, an all-optical 'AND' gate based on a configuration proposed by S. Lee and S.T. Ho [84]. The operation of the gate relies on the formation and propagation of coupled gap solitons by two orthogonally polarised high intensity input beams incident within the bandgap of a FBG [81]. Recently Nuran Dogru was pursueing for the hybrid soliton pulse source (HSPS) developed as a pulse source for the soliton transmission system [88–92]. In a Bragg grating SPM results in the transmission being bistable with one state (high power) having a transmission of unity while in the other (low power) the transmission is vanishingly small [31]. For strong optical pulses this behavior can result in all-optical switching. The all- optical switching of a fiber Bragg grating (FBG) was first seen by LaRochelle et al. in 1990 [67] using a self-written grating centered at 514 nm. In their experiment the probe beam was centered on the grating, while the pump beam had a wavelength of 1064 nm. It was in this vein that Radic, George and Agrawal suggested the use of l/4 phase-shifted gratings for use in optical switching [77]. Ju Han Lee [85–87] demonstrate the use of a superstructured fiber Bragg grating obtain more optimal operation of nonlinear all-optical switches [85], all-optical modulation and demultiplexing systems [86], tunable optical pulse source [87]. In long distance communications, that a third-order nonlinear effect is together with anomalous dispersion, can result in the formation of bright temporal optical solitons. Beacause of the shape-preserving property of the bright and dark solitons, they have received considerable attention from optical communication industries. Solitons are particularly desirable for dtra-long distance communication system and high-bit-rate fiber communications. A challenging possibility is to use fiber gratings for the creation of pulses of slow light, which is a topic of great current interest. A possible way to trap a zero-velocity soliton is to use an attractive finite-size or local defect [83] in BG. The interaction of the soliton with an attractive defect in the form of a local suppression of BG was studied recently in Refs [78,79].

4. Conclusions

My attempt on this article is to give a survey and update some of fiber Bragg grating solitons. There have been two papers for summarizing to Bragg solions [93] and gap solitons [20], gave readers insight into a series of working methods and results before these generalize. Clearly grating solitons have played an important role in past and ongoing nonlinear optical research in fiber Bragg grating, and we believe fiber Bragg grating solions to have their greatest impact in the years to come.

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