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Theoretical Study of Results of Fiber Bragg Grating Solitons

KEYWORDS: kerr nonlinearity, dispersion, grating solitons, Bragg soliton, gap soliton.a

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ABSTRACT *The formation of photo generation 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 results on this field each indicating the potential these solitons have in all optical switching, pulse compression, logic operations and especially important for the optical communication systems.*

1.1.1 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]. 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]. 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] and gap (or Bragg) solitons [10]. 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. 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 co-propagating 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 [4].

As first pointed out by Winful [5], 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 en- tire spectral components of the input pulse lie within the PBG structure, the grating induced dispersion counter- balanced 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 [8] 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 soli- tons and Bragg solitons is hardly maintained and, in general, they are simply called grating solitons [9]. Ul [5], 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

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1.1.2 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 non-linear-coupled mode (NLCM) equations which are non-integrable 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 non- linear 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 [2], is important. Gap solitons are obtained from the NLCM equations and their spectra lie within the pho- tonic bandgap structure. There is another class of solitons called Bragg solitons obtained from the NLS equations whose frequencies fall close to, but out-

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side, 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 [1] 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 [4]. The general gap soliton solutions to the coupled mode equations were first obtained in a limiting case by Christodoulides and Joseph [6]. The solutions were first reported in their most general form by Aceves and Wabnitz [7]. 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. At same time, Sipe and de Sterke ex- amined, in further publications , the pulse trans- mission 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 approxima- tions as well as the description of numerical methods [3] suitable for examining the regimes of instability of these structures. In a word, Sipe and Winful , Christo- doulides and Joseph [6], Aceves and Wabnitz [7], and Winful *et al.* [3] have obtained the analytical solutions for the grating solitons. Comprehensive analyses of Bragg solitons stability have also been re- ported .Still other generalizations have been discussed by Feng and Kneubuhl [5] and by Feng [6]. In order to better simulate experimental conditions, Broderick, de Sterke and Jackson presented a method of numerically modeling periodic structures having optical nonlinearities [7]. Other important extensions and generalizations include a series of papers by Aceves and coworkers extending many of these principles to waveguide arrays [3].

Inverse scattering transform (IST) is currently the standard analytical technique for obtaining the soliton solution for the homogenous NLSE [9]. 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 soli- tons [3]. 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 [7], hence that an EPP would be more accurate in that case . How ever, previously, gap soliton propagation in the presence of uniform gain and loss was succesfully treated using an EPP [7] method, which was also used by Capobianco et al. to treat propagation between two quadratically nonlinear materials [8]. 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 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.* [5]. 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 [12]. 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 [12]. 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% [11].

1.2.1 Conclusions

Clearly grating solitons have played an important role in past and ongoing nonlinear optical research in fiber Bragg grating and I believe fiber Bragg grating solitons to have their greatest impact in the years to come.

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