Optics Communications 339 (2015) 194–208

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Efficient method of calculation of Raman soliton self-frequency shift in nonlinear optical media

Jacques Atangana [a,c,e,*], Bibiane Mireille Ndi Nnanga [b,e], Bedel Giscard Onana Essama [c,a,e], Bouchra Mokthari [d,e], Noureddine Cherkaoui Eddeqaqi [d,e], Timoleon Crepin Kofane [e,b]

[a] Department of Physics, Higher Teacher's Training College Yaounde, University of Yaounde I, P.O. Box 47 Yaounde, Cameroon
[b] Laboratory of Mechanics, Department of Physics, Faculty of Science, University of Yaounde I, P.O. Box 812 Yaounde, Cameroon
[c] Laboratory of Electronics, Department of Physics, Faculty of Science, University of Yaounde I, P.O. Box 812 Yaounde, Cameroon
[d] Department of Physics, Faculty of Science, Moulay Ismail University, Meknes, Morocco
[e] Centre d'Excellence Africain des Technologies de l'Information et de la Communication (CETIC), Université de Yaoundé I, Cameroon

A R T I C L E I N F O

Article history:
Received 11 September 2014
Received in revised form
11 November 2014
Accepted 13 November 2014
Available online 17 November 2014

Keywords:
Cubic-quintic Raman effects
Soliton self-frequency shift
Modified ansatz
Collective *coordinates*

A B S T R A C T

We present a method to evaluate Raman soliton self-frequency shift of soliton light pulses solution for higher-order nonlinear Schrödinger equation with non-Kerr nonlinearity which propagate in high-bit-rate optical systems. We show that the conventional technique, known as collective *coordinates* theory, becomes inappropriate and leads to a qualitatively and unpredictable dynamics of collective coordinates. We resolve this changeableness by reformulating the conventional technique during which we add two appropriate pulse parameters called the simulated Raman scattering specific coordinates. We point out the use of these coordinates by applying them to a correct *calculation* of soliton self-frequency shift (SSFS) and temporal shift *when* cubic-quintic effects effectively act. This method of *calculation* of soliton self-frequency shift could be an interesting physical tool to those working on propagation of nonlinear pulses in *optical* media where the investigations of simulated Raman scattering with associated phenomena are required.

1. Introduction

Activities in optical communication systems operating with ultrashort light pulses require several processes, numerical simulations [1–6] and various types of optical components, generally not necessary at lower bit rates [7]. It becomes fundamental in such *case* to design the key elements of the communication systems best adapted *from numerical simulations*, *in order* to characterize the light pulse parameters. For example, the spectral bandwidth obtained from the pulse's temporal width and chirp [8–17] requires the knowledge of the light pulse phase behavior which essentially depends on the calculation of two major pulse parameters *such as* the chirp and the pulse frequency shift with respect to the carrier frequency (say ω_0). However, it is difficult to ascertain directly from the original field what will really happen in the system and during the propagation [17–19], the field will describe all perturbations present in the real system. Consequently, *it becomes crucial to develop a method able to provide qualitative information about the behavior of the field solution of nonlinear Schrödinger equation considered. This method is chosen to describe the evolution of several integral quantities of the field solution*. To the best of our knowledge, the so-called "method of moment for nonlinear Schrödinger equation" [20], with its possibilities to reduce the problem to a system of coupled ordinary nonlinear differential equations is one of the best candidate for this approach. Furthermore, the method provides approximations which receive different names depending on the specific field of application: time-dependent variational method, collective coordinates method, the averaged Lagrangian [21,22] and the so-called quadratic phase approximation [20]. The results shown for the evolution of the field solution using the moments method are exact and in some sense rigorous. However, in many situations of practical interest, we can approximate the phase of the field solution by a quadratic functions of coordinates best adapted to accurately characterize the chirp and the frequency shift observed during the dynamics of the field solution. Otherwise, ansatz functions associated and conventionally used until now to describe this dynamics in specific cases of propagation of ultrashort light pulses in

* Corresponding author at: Department of Physics, Higher Teachers Training College, University of Yaoundé I, Yaoundé, Cameroon.
E-mail addresses: atanganajaques@yahoo.fr (J. Atangana), mireille042005@yahoo.fr (B. Mireille Ndi Nnanga), onanaessama@yahoo.fr (B. Giscard Onana Essama), nicet2012@hotmail.com (B. Mokthari), echerkaoui@hotmail.com (N.C. Eddeqaqi), tckofane@yahoo.com (T.C. Kofane).

http://dx.doi.org/10.1016/j.optcom.2014.11.050
0030-4018/

optical communication networks have as common feature, the consideration of a standard quadratic phase [2,9–19]. The goal of these ansatze which depends on of linear and nonlinear effects identified in the model is to give a good reconstruction of the light pulse profile from the dynamics of its collective coordinates. Some well-known examples of such reconstructions have been illustrated to describe the dynamics of soliton light pulses such as the propagation of light pulses asymmetrically distorted by the third-order dispersion [17] and the behavior of light pulses symmetrically distorted by the fourth-order dispersion [18]. Unfortunately, it clearly appears that the choice of these ansatze function, having a standard quadratic phase, is not sufficient to give a correct description of intra-pulse Raman scattering where high- and low-frequency components of an optical pulse pump transfer energy to the red side through stimulated Raman scattering. This deficiency was already perceived by some authors who suggested to use the moment method [20–22] in order to study the effect of frequency chirp on the Raman-induced frequency shift in the cases of both normal and anomalous dispersion. Then, the method was used by many authors to investigate the behavior of optical pulses when several physical phenomena should occur during the propagation. One can enumerate the development of a general theory of intra-pulse Raman scattering to evaluate the effects of frequency chirp on Raman-induced frequency shift [22]. Besides, the so-called soliton self-frequency shift occurring as a result of the red-shift induced by this intra-pulse Raman scattering [23–29] presents many wide applications. If one can discern among them the soliton self-frequency shift evaluation and its control including its suppression from a use of bandwidth-limited amplification [22], or upshifted filtering [15], the important application is supercontinuum generation in various media. Fundamentally the dynamics of supercontinuum generation process comes from the pivotal role played by the interaction between higher-order dispersion and nonlinearity when ultrashort optical pulses are launched in the anomalous group-velocity dispersion domain. The phenomenon which involves the dynamics of several solitons and dispersive waves (radiations) in photonic crystal fibers has attracted considerable attention since its wide applications ranging from spectroscopy, metrology, telecommunications [30–36] and the dynamics of Raman soliton [37]. Besides, the influence of the simultaneous action of higher-order effects including intra-pulse Raman scattering, higher-order dispersion, self steepening or quintic nonlinearity, to describes the propagation of ultrashort pulses in optical fibers has been extensively studied by many authors. The investigation of Tsoy and Sterke [30] is based on the soliton's adiabatic dynamics in optical fibers in the presence of the third-order dispersion, self-steepening and Raman effects. Judge et al. have shown theoretically that dispersive waves resonantly emitted by a soliton in the presence of negative third-order dispersion may be temporally trapped and red-shifted [38]. Sorensen et al. show that the soliton is able to keep more of the energy of its dispersive wave trapped when the gradient of the taper is decreased. This was explained as a group-acceleration mismatch of the soliton and dispersive wave induced by the taper [39]. The paper of Stephen and Dekker has demonstrated a record soliton self-frequency shift of a spectrally isolated soliton over more than an octave, from 801 nm to 1708 nm using a specially selected photonic crystal fibers with reduced OH loss [40]. It is observed in the majority of these papers that the authors used the complete response function of the Raman effect to study the case of negative third-order dispersion aiming to explain the suppression of the Raman self-frequency shift observed in the experiment where, the self-steepening effect could be omitted [41]. But in many investigations, studies are focussed on the separate influence of Raman scattering and third-order dispersion as well as the combined action of these effects with self-steepening [30]. However some methods of analysis and the range of applicability used until now have as common focal points the supercontinuum generation, the exploitation of the soliton self-frequency shift in the realization of pulsed wavelength tunable sources, its cancelation by resonant emission of normally dispersive waves, the enhancement or the soliton self-frequency shift performance in highly nonlinear chalcogenide, as well as other nonlinear processing applications and the well-known physical concept effect named group-acceleration mismatch [30–40]. However, if the efficient practical method to calculate the soliton self-frequency shift uses the method of moment [20–22], it is also observed that some physical specific pulse parameters able to give a qualitative detailed picture of the role and mode of singular or simultaneous action of some selected higher-order terms (such as third-order dispersion, self-phase modulation, quintic nonlinearity, self-steepening, or stimulated Raman scattering) require an important amount of calculation with these method using the exact pulse field throughout the pulse propagation. The use of the variational analysis presents two major advantages. Firstly, the pulse propagation can be completely characterized without having to know the exact pulse field. Secondly, the role and mode of action of each perturbed pulse parameter can be given in detail. The only drawback of this method is its level of accuracy, which strongly depends on the choice of specific parameters of the ansatz function. More so, it becomes crucial to consider an ansatz function including additional terms able to describe the action of some selected linear and nonlinear terms on the light pulse propagation.

In this paper, we present an extended analytic theory of the Raman self-frequency shift in a theoretical optical environment with a very weak quintic nonlinearity where third-order dispersion and self-steepening effects are omitted [41]. The main goal being to evaluate the dynamics of collective coordinates on the predicted evolution of the soliton light pulse when some selected effects act in the optical system. For this end, The variational method is used with a specific modified conventional ansatz including two additional higher-order phase terms. The first one corresponds to the description of frequency fluctuations while the second completes the chirp dynamics in order to give a good description of the temporal shift.

The paper is organized as follows. In Section 2, the modified conventional ansatz is presented and the collective coordinates technique is applied in order to give the analytical expressions of variational equations. Section 3 embodies a development of numerical simulations in order to obtain a careful evaluation of the dynamics behavior of light pulse specially the temporal and frequency shift when the stimulated Raman scattering and non-Kerr effects come into play in a high bit rate and long-distance transmission system. A conclusion is made in Section 4.

2. Collective coordinates for light pulse with cubic-quintic Raman effects

2.1. Theoretical model

We consider the dynamics of solitary wave solutions for an interesting nonlinear Schrödinger equation including some selected higher-order terms which can be written in terms of slowly varying envelope of electric field $\psi(z, t)$ as follows [15,23,26,42–45]:

$$\frac{\partial\psi}{\partial z} + i\frac{\beta_2(z)}{2}\frac{\partial^2\psi}{\partial t^2} - i\gamma_0(z)|\psi|^2\psi - i\gamma_q(z)|\psi|^4\psi = i\gamma_r(z)\left(\frac{\partial|\psi|^2}{\partial t}\right)\psi + i\gamma_{qr}(z)\frac{\partial}{\partial t}(|\psi|^4)\psi \quad (1)$$