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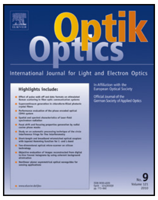

Role of parametric gain operator for the higher-order nonlinear Schrodinger equation

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ABSTRACT

Based on the separate discussions on dispersion and nonlinear effects, the parametric gain operator is established to exhibit the pump field's impact in the process of the fast and wide spectral expansion. The condition of inducing sideband is that $\sin[\sum_{n=2}^{\infty}\frac{(-1)^{n+1}}{n!}\beta_n\omega^n dz]=0$ has a solution with the intensity fluctuations or $\cos[\sum_{n=2}^{\infty}\frac{(-1)^{n+1}}{n!}\beta_n\omega^n dz]=0$has a solution with a initial phase. The initial intensity fluctuation results in a coherent white source while the initial phase modulation cuts down this band's width but brings the nearby blue-shift or red-shift solitons which depend on the dispersion coefficients. Furthermore, this parametric gain operator can be used to describe the phenomenon of CW pump inducing solitons.

1. Introduction

Supercontinuum(SC) light sources have been widely studied, but the mechanisms leading to the rapid and extreme spectral expansion of the pump signal are not well understood. A crucial insight into the mechanisms underlying SC fluctuations have been provided by Solli et al. who used a novel wavelength to time conversion technique to directly measure the statistics of the shot to shot SC noise [1]. The continuum formation process accompanied with a cascade of Stokes Raman shifts acts as a source of solitons that evolved from modulation instability(MI). Subsequently, the solitons experience Raman gain, collisions and self Raman interactions leading to long wavelength broadening [2]. Numerical simulations and experimental measurements have showed that, when a train of pulses was generated, strong ionization of the gas occurred. This extreme MI can be used to experimentally generate a high energy and spectrally broad SC extending from the deep ultraviolet to the infrared [3].

An aspect of SC generation in photonic crystal fiber(PCF) has been that the spectrum bandwidth and uniformity were improved because of its sensitivity to noise [4]. In the femtosecond regime, the introduction of an initial positive chirp is helpful for the increase of the continuum bandwidth and vice versa. An optimum positive chirp parameter exists corresponding to the maximum spectral bandwidth. In the picosecond regime, however, the SC spectral shape and bandwidths

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are almost the same for various initial chirp parameters [5]. Additionally, numerically investigation indicated that increasing the spectral linewidth of the pump decreased the SC spectral width. MI gain will be completely eliminated when the pump bandwidth is equivalent to the MI bandwidth [6]. The interplay between the effects of MI and stimulated Raman scattering (SRS) has been validated via experimental results and resulted in a spectral broadening from 1350to 1700 nm [7]. On the other hand, the Stokes bands falling within the normal dispersion regime and without undergoing significant spectral broadening or soliton self-frequency shift dynamics while cascaded anti-Stokes Raman generation due to phase-matching allowed by the group-velocity dispersion, was also reported in [8].

Experiment demonstrated that continuous-wave(CW) SC generation in optical fibers was significantly enhanced by using both multi-wavelength pumping and dispersion management where Raman-assisted MI, soliton compression and dispersion wave generation were induced [9]. The intensity fluctuations characteristic of temporal partial coherence CW pump sources individually drove the continuum formation. For sources with sufficiently low coherence, these solitons actually underwent fission rather than MI, changing the nature of the CW supercontinuum evolution [10].

Some investigations adopted the generalized NLSE based on the slowly varying approximation [11]. But the SC generation is a fast spectral expansion process, and it means the nonlinear coefficients determined by the transverse field's distribution are not constants and the approximation of the Raman gain as a linear function of frequency is not valid any more [12–14]. The corresponding adjustments with the transverse effect [15] and the second order partial differential of the longitudinal to z should be directly added into the equation, are required [16]. Finally, it becomes unsolvable.

In this paper, we will separately adopt the results of dispersion and nonlinear effects on the field and build up the general parametric gain(PG) operator for the analyses of SC generation, and thus it avoids the complex calculation and building of modified NLSE [17]. Even in the case of fast varying envelope, the dispersion and nonlinear effects still affect the field at the same forms when we calculate the field with sufficient short time and distance durations. For the initial stage, this treatment to calculate the parametric gain is obviously reasonable.

2. Parametric gain operator

Taking the high order dispersion and nonlinear effects into account, the complex envelope of the pump field $\tilde{\varepsilon}(z,t)$ satisfies

$$\begin{aligned}&\frac{\partial\tilde{\varepsilon}}{\partial z}=\sum_{n=2}^{\infty}\frac{(-i)^{n+1}}{n!}\beta_n\frac{\partial^n}{\partial t^n}\tilde{\varepsilon}-\frac{\alpha}{2}\tilde{\varepsilon}+\\&\sum_{k=1}^{\infty}[a_k\left|\tilde{\varepsilon}\right|^{2k}\tilde{\varepsilon}+b_k\frac{\partial}{\partial t}(\left|\tilde{\varepsilon}\right|^{2k}\tilde{\varepsilon})+c_k\frac{\partial}{\partial t}(\left|\tilde{\varepsilon}\right|^{2k})]\end{aligned}\qquad(1)$$

whereβ_n are various dispersion coefficients at the pump frequency ω_0 . a_k, b_k and c_k are various nonlinear coefficients. Strictly, all these coefficients are functions of ω in the process of SC generation, but in the start point of the PCF where MI dominates, they can be treated as constants.

Even the launched pump field is not CW, the results at the terminal will approach the same not for very long highly nonlinear fibers(HNLF), so for simplification, at the fiber input, a continuous wave with a high power is transmitted. At distance z, the extra phase induced by SPM effect can be represented as:

$$\varphi(z,\omega)=i\int_0^z\sum_{k=1}^{\infty}Im[a_k+b_k(-i\omega)+c_k(-i2\omega)]P_0^ke^{-\alpha z}dz\qquad(2)$$

Where ω is the frequency shift. Dispersion effect can be described by the matrix:

$$\begin{vmatrix}\cos[\sum_{n=2}^{\infty}\frac{(-1)^{n+1}}{n!}\beta_n\omega^n dz] & -\sin[\sum_{n=2}^{\infty}\frac{(-1)^{n+1}}{n!}\beta_n\omega^n dz]\\ \sin[\sum_{n=2}^{\infty}\frac{(-1)^{n+1}}{n!}\beta_n\omega^n dz] & \cos[\sum_{n=2}^{\infty}\frac{(-1)^{n+1}}{n!}\beta_n\omega^n dz]\end{vmatrix}\qquad(3)$$

The intensity fluctuation directly from (1) is

$$\Delta P=\sum_{k=1}^{\infty}P_0^k\int_0^z\exp\{2Re[a_k-i\omega b_k-i2\omega c_k]dz-\alpha dz\}\qquad(4)$$

And another fluctuation induced by the dispersion and nonlinear effects is [18] :

$$\Delta P'=-2P_0e^{-\alpha z}\sin[\sum_{n=2}^{\infty}\frac{(-1)^{n+1}}{n!}\beta_n\omega^n dz]\varphi(z,\omega)\qquad(5)$$