Supercontinuum generation study through the RK4IP method

CARRILLO-DELGADO, Carlos Moisés†', HERNANDEZ-GARCIA, Juan Carlos*'', ESTUDILLO-AYALA, Julian Moisés', LAUTERIO-CRUZ, Jesús Pablo', POTTIEZ, Olivier''', MARTINEZ-ANGULO, José Ramón' and ROJAS-LAGUNA, Roberto'

'Universidad de Guanajuato, División de Ingenierías Campus Irapuato-Salamanca, Carretera Salamanca-Valle de Santiago km 3.5+1.8 km, Comunidad de Palo Blanco, Salamanca, Gto., C.P. 36885, México.
''Cátedras CONACyT, Av. Insurgentes Sur No. 1582, Col. Crédito Constructor, Del. Benito Juárez, C.P. 03940, México.
'''Centro de Investigaciones en Óptica (CIO), Loma del Bosque 115, Col. Lomas del Campestre, León Gto., 37150, México.

Recived January 11, 2017; Accepted May 8, 2017

Abstract

In this paper we simulate the spectral broadening of an ultrashort pulse propagated into different lengths of standard single-mode fiber (SMF), by solving the generalized nonlinear Schrodinger equation (GNLSE), through the Fourth Order Runge–Kutta in the Interaction Picture (RK4IP) method. Here, it is possible to observe, by simulation or computational analysis, supercontinuum generation during the propagation of a pulse into a single mode optical fiber by the accumulation on nonlinear phonomena. Also, it is possible to predict its time and spectral behaviour.

Supercontinuum Generation, Numerical Analysis, Nonlinear Optics

Citation: CARRILLO-DELGADO, Carlos Moisés; HERNANDEZ-GARCIA, Juan Carlos; ESTUDILLO-AYALA, Julian Moisés; LAUTERIO-CRUZ, Jesús Pablo; POTTIEZ, Olivier; MARTINEZ-ANGULO, José Ramón and ROJAS-LAGUNA, Roberto. Supercontinuum Generation in diffetrent lenghts of SMFthrough the RK4IP method. ECORFAN Journal-Taiwan. 2017, 1-1: 14-17

*Correspondance to Author (email: jchernandez@ugto.mx)
† Researcher contributing as first author.

Introduction

Supercontinuum generation (SCG) is a nonlinear phenomenon as result of the sum of accumulative nonlinear effects. Although an optical fiber is made generally of silica and this material has a low nonlinear coefficient, the sum of all phenomena all along a large distance of fiber produces interesting phenomena, for instance solitonic effects, spectral broadening, and rogue waves (Akhmediev et al., 2013). The relevance to develop better supercontinuum light sources relies on their applications: optical communications, spectroscopy, optical pulse compression, imaging and microscopy, among others (Alfano, 2016). Our interest is focus to study the propagation of pulses through optical fibers with the purpose of generate flat spectrum and broadening spectrum (Estudillo-Ayala et al., 2012). In this paper, in a numerical way and through the RK4IP (Hult, 2007) algorithm, we achieved SCG using SMF with low peak powers (<5 W), as well as pulses of soliton shape (hyperbolic secant). Nonetheless, this study can be extended to non-common shapes like noise-like pulses (NLPs) and high energetic peak powers (>1 kW). Analyze and predict the behavior of pulses propagating in a SMF. Study how to produce or generate supercontinuum spectrum.

Methodology

Pulse propagation through a medium implies the solution of the Nonlinear Schrödinger Equation (NLSE), or in our case, the Generalized (GNLSE). Rewriting the GNLSE in terms of the interaction picture method, we have, equation (1):

$$\frac{\partial A}{\partial z} = \left(\widehat{D} + \widehat{N}\right)A \tag{1}$$

where $A(z,T)$ is the complex field envelope in the z direction, T is the retarded time traveling at the envelope group velocity, and the operators $\widehat{D}$ and $\widehat{N}$ represent the dispersive and the nonlinear terms, respectively. The approximation is given at equation (2) and it is used for implementing the numerical method (Hult, 2007):

$$A_1 = \exp\left(\frac{h}{2}\widehat{D}\right)A(z,T) \tag{2}$$

This method consists on separate the problem on different steps, where at the beginning the pulse start propagating into the medium, in our case an optical fiber of length L; it is taken a piece of the fiber broken in a step h and the dispersion is solved at this point. So, this is, equation (3).

$$k_1 = \exp\left(\frac{h}{2}\widehat{D}\right)A(z,T)[h\widehat{N}(A(z,\mathrm{T}))]A(z,T)$$

$$k_2 = h\widehat{N}\left(A_1 + \frac{k_1}{2}\right)\left[A_1 + \frac{k_1}{2}\right]$$

$$k_3 = h\widehat{N}\left(A_1 + \frac{k_2}{2}\right)\left[A_1 + \frac{k_2}{2}\right]$$

$$k_4 = h\widehat{N}\left(\exp\left(\frac{h}{2}\widehat{D}\right)(A_1 + k_3)\right) \times \left(\exp\left(\frac{h}{2}\widehat{D}\right)(A_1 + k_3)\right) \tag{3}$$

The RK4IP method uses the Fast Fourier Transform (FFT) determining the dispersion effect in the frequency domain.

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Then the field solution is transformed to give the final solution, which can be written as:

$$A(z+h,T) = \exp\left(\frac{h}{2}\widehat{D}\right)\left[A_1+\frac{k_1}{6}+\frac{k_2}{3}+\frac{k_3}{3}\right]+\frac{k_4}{6} \quad (4)$$

As the parameters implemented for the computational study, we vary the length of the SMF: 1, 10 and 500 km; the fiber dispersion is D = 17 ps/nm/km and the nonlinear coefficient is γ = 1.5/W/km.

Results and Discussion

Figures 1 and 2 present simulations of the pulse propagating into the optical fiber; the results show, three stages of the same pulse only varying the length of the fiber, starting with 1 km, then 10 km and finally 500 km. The number of cycles for each computational case was 500.

In Fig. 1 is demonstrated the accumulation of nonlinear phenomena all along the length of the fiber (Agrawal, 2011), where by dispersive effects, is produced Self Phase Modulation (SPM). In the beginning of the SMF in Fig. 1(a), a solitonic effect is appreciated. Thus, energy travel slowly in the fiber generating the broadening of the spectrum, as depicted in Fig. 2. Something remarkable from the simulation are the dark regions where in between the center of the pulse originally propagating; those fringes remain at the lower energy by the total length of the fiber was 500 km (Fig 1(c)), is something than can be appreciated clearly in Fig 1(a) or 1(b).

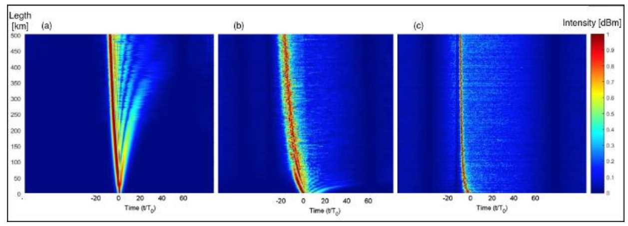

Figure 1 Simulation of a hyperbolic secant pulse propagating into a single mode optical fiber with a peak power of 50 mW; (a) in the simulation of 1 km of fiber it can be appreciated solitonic effects; (b) in the simulation for 10 km, the energy of the pulse shifts to the blue, and appear new components; (c) for 500 km of fiber, the pulse shifts completely to a new temporal region, broadening the spectrum. At this point, it is important to note that are the dark or lower energies remain constant from all the fiber length.

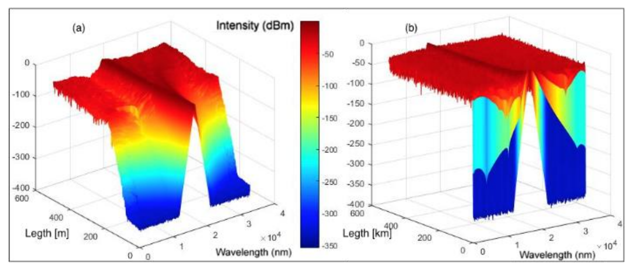

Figure 2 Spectral behavior of the pulse, where is possible to appreciate the broadening of the spectrum, (a) in the 1 km case, (b) and in the 500 km case.

Conclusions

In this work, through the RK4IP method, the spectral and temporal behavior of an ultrashort pulse, propagating into some pieces of SMF was shown. The simulated fiber lengths were 1, 10 and 500 km. Nonlinear phenomena were formed such as: solitonic effects, spectral broadening, and SPM. The wavelegth was centered on 1550 nm, and the peak power was 50 mW. Those parameters were proposed, to get an approach on than we could have experimentally.

Ackowledgments

C.M. Carrillo-Delgado was supported by the CONACyT grant No. 245146. This work was funded by Cátedras-CONACyT project 3155 and Ciencia Básica project No. 257691.

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ISSN 2524-2121