SOLITON OPTICAL FIBERS SUPERCONTINUUM GENERATION NEAR THE ZERO DISPERSION

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ABSTRACT

During the last decade, the development of supercontinua (SC) sources has emerged as an interesting and active research field. This is largely due to new technological developments, which have allowed more controlled and accessible generation of supercontinua.

In this paper we study the dynamics of Raman soliton during supercontinuum process when the pulse experiences initially normal group velocity dispersion with a negative dispersion. In this situation, the blue components of the spectrum form a Raman soliton moves faster than the input pulse because of Raman induced frequency downshifting ceases to occur as the spectrum of Raman soliton approaches the zero dispersion point.

From this study one can distinguish that the first order bright soliton pulse depends on two important bases: first depends on the contents of the optical fibers and building method, where it is accomplished by making a balance between the dispersion effect and the nonlinear effect. The second depends on the parameters for mode and the starting point of the pulse shape inside the fiber such as the pulse width, normalized propagation distance and the existence of any nonlinear external effect.

Keywords: Group velocity dispersion, Optical fiber, Soliton, Supercontinuum.

I. INTRODUCTION

In optics, a supercontinuum (SC) is formed when a collection of nonlinear processes act together upon a pump beam in order to cause severe spectral broadening of the original pump beam. The result is a smooth spectral continuum (see figure 1 for a typical example) [1].
Supercontinuum generation in photonic crystal fibers (PCF) has attracted considerable attention in recent years because of its wide applications ranging from spectroscopy and metrology to telecommunications. Extensive studies reveal that several physical phenomena are involved in the process of SC generation when an ultrashort optical pulse experiences anomalous dispersion and undergoes enormous spectral broadening during its propagation inside a PCF. Self-phase modulation (SPM), intra-pulse Raman scattering (IPRS), four wave mixing, cross-phase modulation (XPM), modulation instability, and dispersive wave (DW) generation are the major nonlinear processes that take part actively during SC generation [2].

The interplay between the dispersion and nonlinearity of the waveguide produces optical solitons whose dynamics play a pivotal role in the process of SC generation when an ultrashort optical pulse is launched in the anomalous group velocity dispersion (GVD) domain. In particular, the ideal periodic evolution of a higher order soliton is perturbed by third and higher order dispersions (HOD) to the extent that it breaks into its fundamental components, a phenomenon known as soliton fission. These fundamental solitons experience induced red shifts, and this shift is largest for the shortest soliton with the highest peak power, also called the Raman soliton. During the fission process, HOD terms lead to transfer of energy from the soliton to a narrowband resonant DW, also called non-solitonic radiation. This DW is emitted on the blue side of the original pulse spectrum for positive values of third order dispersion and is of considerable practical importance for generating blue shifted radiation [2-4]. The interaction between the soliton and the DW turns out to be quite interesting and it has been studied extensively in recent years with an analogy to gravity like potential.

Though nonlinear propagation of ultrashort laser pulses in dispersive single mode optical fibers has steadily been investigated over the last three decades, studies on continuous wave (CW) partially coherent light have been scarce. It is well known that dispersive properties of the PCF play a governing role in producing the DW and controlling the SC generation. Recent developments in PCF technology have made it possible to observe new regimes of nonlinear pulse propagation because such fibers exhibit fascinating dispersion.
profiles with enhanced nonlinearities. An appropriate design of a PCF not only shifts the zero
dispersion wavelengths (ZDW) toward shorter wavelengths but also produces dispersion
profiles with multiple ZD points, features unattainable with conventional fibers [2]. Unusual
soliton dynamics are expected when an ultrashort optical pulse is launched in the vicinity of a
ZD point since the broadened pulse spectrum experiences opposite types of dispersion across
the ZD point.

II. WAVE PROPAGATION IN FIBERS

No presentation of nonlinear phenomena in fibers can be done without considering the
implications of the polarization, on the propagation. The wave equation for the field is [5]:

$$\nabla^2 E - \frac{1}{c^2} \frac{\partial^2 E}{\partial t^2} = -\mu_0 \frac{\partial^2 P_L}{\partial t^2} - \mu_0 \frac{\partial^2 P_{NL}}{\partial t^2}$$

(1)

Where: \( \tau \) is the time with the polarization terms from:

\[ P = \varepsilon_0 (\chi^{(1)} E + \chi^{(2)} EE + \chi^{(3)} EEE + ...) \]

separated into the linear part, \( P_L \) and the nonlinear part, \( P_{NL} \). Tackling (1) for a general system in the vector form is a formidable task. However, we can still express a wealth of phenomena with some simplifying assumptions. Assume the polarization remains the same throughout propagation, temporal retarded effects (such as stimulated Raman scattering and stimulated Brillouin scattering) represent only a perturbation and are introduced to (1). Neglecting polarization changes allows a simple scalar treatment to be used. It also simplifies the treatment of the susceptibility \( \chi \). The nonlinear polarization becomes [5]: \( P_{NL} = \chi^{(3)} E E E \). Assuming the spectrum of the electric field is centered around the frequency \( \omega_b \), \( \beta (\omega) \) can be expanded in a taylor series [5]:

$$\beta (\omega) = n(\omega) \frac{\omega}{c} = \beta_0 + \beta_1 (\omega - \omega_b) + \frac{1}{2} \beta_3 (\omega - \omega_b)^2 + ...$$

(2)

where \( \beta_m \) represents the \( m \)th derivative of the propagation constant with respect to \( \omega \) [5]:

$$\beta (\omega) = \left( \frac{d^m \beta}{d \omega^m} \right)$$

(3)

The first order term, \( \beta_1 \), describes the motion of the pulse envelope, and is related to the
group velocity by \( \beta_1 = v_g^{-1} \). All higher order terms describe the dispersion of the medium.
The dominant contributions come from the second order term \( \beta_2 \) also called GVD and the
third order term \( \beta_3 \), also called simply third order dispersion. For completeness, \( \beta_2 \) is related
to the dispersion coefficient defined as [5]: \( D = -\frac{2 \pi c}{\lambda^2} \beta_2 \).
III. SOLITON FISSION REGIME

In the soliton fission regime a short, high power, femtosecond pulse is launched into the photonic crystal fiber or other highly nonlinear fiber. The femtosecond pulse may be considered as a high order soliton, consequently it rapidly broadens and then fissions into fundamental solitons. During the fission process excess energy is shed as dispersive waves on the short wavelength side. Generally these dispersive waves will undergo no further shifting and thus the extension short of the pump is dependent on how broadly the soliton expands as it breathes [6,7]. The fundamental solitons then undergo intra-pulse Raman scattering and shift to longer wavelengths (also known as the soliton self-frequency shift), generating the long wavelength side of the continuum. It is possible for the soliton Raman continuum to interact with the dispersive radiation via four wave mixing and cross-phase modulation. Under certain circumstances, it is possible for these dispersive waves to be coupled with the solitons via the soliton trapping effect. This effect means that as the soliton self-frequency shifts to longer wavelengths, the coupled dispersive wave is shifted to shorter wavelengths as dictated by the group velocity matching conditions. Generally, this soliton trapping mechanism allows for the continuum to extend to shorter wavelengths than is possible via any other mechanism [6-9].

We can define a soliton fission length, \( L_{fiss} \), to estimate the length at which the highest soliton compression is achieved, such that [10]:

\[
L_{fiss} = \frac{L_D}{N} = \left( \beta_2 \tau_0^2 \right) \frac{\tau_0^2}{\tau^2},
\]

where \( L_D \) is the characteristic dispersion length, \( N \) is the soliton order and \( \tau \) is the minimum pulse width. As fission tends to occur at this length then provided that \( L_{fiss} \) is shorter than the length of the fiber and other characteristic length scales such as the modulation instability length, fission will dominate [10].

IV. SIMULATION RESULT AND DISCUSSION

We proceed with the supercontinuum generation near the zero dispersion using MATLAB which is a great and easy tool to use to simulate optical electronics. Supercontinuum sources based on the extreme broadening of laser pulses in nonlinear photonic crystal fibers have been predicted to be a very interesting technology in the scientific as well as the industrial communities. The first supercontinuum generated in PCF operated in this regime and many of the subsequent experiments also made use of ultrashort pulsed femtosecond systems as a pump source. One of the main advantages of this regime is that the continuum often exhibits a high degree of temporal coherence; in addition it is possible to generate broad supercontinua in very short lengths of PCF.

All the results below are got after following these steps:

1- Generalized the Nonlinear Schrödinger Equation NLSE.
2- Calculate the attenuation coefficient.
3- Applied the Taylor expansion.
4- Found the time domain field and time domain intensity.
5- Implementation of group velocity dispersion relation.
Figure 2 (a) time and (b) input file spectra versus the wavelength respectively. In the case of (a), mean= -3.073E-016, mode= -6.25 and the slandered deviation (STD) = 3.609. While in (b) mean= 0.7137, mode= 5.317E-094 and the STD= 6.703.

Figure 2 (a) Time versus the wavelength. (b) The input field spectra versus the wavelength.

Supercontinuum generation is a process in which multiple colors are generated through the nonlinear interaction of the laser pulse with the material. The longer the interaction length, the larger amount of nonlinear interaction. We will see that the length scale over which nonlinear effects are manifested is not typically limited by the fiber length, but by other effects such as dispersion. Figure 3 (a) time domino intensity versus the wavelength, (b) the spectral intensity versus the wavelength for different soliton order.

Figure 3 (a) Time domino intensity versus the wavelength. (b) The spectral intensity versus the wavelength.

Figure 4 shows the distance versus wavelength. It explains the temporal evolution of an optical pulse launched in the normal dispersion domain close to the ZD wavelength. Although SC generation in the case of anomalous GVD has been studied extensively, much less attention has been paid to the case of normal GVD. In soliton fission fundamental solitons experience intra-pulse Raman scattering induced red shifts, and this shift is largest for the shortest soliton with the highest peak power, also called the Raman soliton. During the fission process, high order dispersion terms lead to transfer of energy from the soliton to a narrowband resonant DW, also called non-solitonic radiation. This DW is emitted on the blue side of the original pulse.
Figure 4 Distance versus the wavelength for deferent numbers of soliton order.

Figure 5 explain the relationship between the distance and delay. It show the spectral evolution of an optical pulse launched in the normal dispersion domain close to the ZD wavelength. Numerical simulations shown in Fig. 6 reveal that bending of the temporal trajectory occurs earlier and quicker with increasing values of \( N \) soliton order. This is expected because IPRS increases with the soliton order, producing larger red shifts. The DW on the other hand accelerates rapidly with increasing soliton order. Since DW never overlaps with the Raman soliton, it is not trapped by this soliton. These features are clearly seen in Fig. 6 where we show temporal evolution for deferent values of \( N \).

Figure 5 Distances versus the Delay for deferent numbers of soliton order.

V. CONCLUSION

From the results above, numerical features are revealed when a picosecond pulse is launched in the normal GVD region with a monotonous dispersion slope. The nonlinear pulse broadening phenomenon of supercontinuum generation in fibers has been the subject of much recent research. In this paper we have focused on the supercontinuum process taking place when a picosecond pulse is launched close to the ZD wavelength of a fiber. We discuss soliton dynamics in the light of group delay curve when input pulse is launched exactly at the ZD. For a negative value of third order dispersion (TOD), the Raman soliton is formed by the blue components of the pulse falling in the anomalous GVD regime and it exhibits unusual dynamics by pulling its counterpart in the red region of the spectrum. In the case of a positive
TOD, optical soliton is formed by the red components of the pulse and is found to interact with its counterpart via cross-phase modulation during propagation inside the PCF, resulting in a spectral pushing. Unusual dynamics of the Raman soliton is observed when the pulse is launched in the normal dispersion domain with a negative TOD. In this situation, the blue components of the pulse form a Raman soliton that moves faster than the signal pulse. However, as it is red shifted through IPRS, it gradually begins to decelerate. This deceleration stops when the soliton spectrum approaches the ZD point because of a cancellation of the Raman induced spectral shift.

REFERENCES