Optics Communications 359 (2016) 20–25

Contents lists available at ScienceDirect

Optics Communications

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

# The impact of self-steepening effect on soliton trapping in photonic crystal fibers

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ARTICLE INFO

*Article history:*
Received 24 July 2015
Received in revised form
1 September 2015
Accepted 4 September 2015

*Keywords:*
Supercontinuum
Self-steepening
Photonic crystal fiber
Soliton

ABSTRACT

We present a numerical investigation of self-steepening (SS) effect on trapping of dispersive waves by solitons during supercontinuum (SC) generation in anomalous dispersion regime in photonic crystal fibers with two zero dispersion wavelengths. It is demonstrated that with the increase of SS coefficient, the power ratio of red-shifted dispersive waves (R-DWs) is weakened greatly whereas the power ratio of blue-shifted dispersive waves (B-DWs) is enhanced, which means that SS effect leads to the energy redistribution between solitons and DWs, as a consequence, the soliton trapping of DWs is also influenced. Trapping of R-DWs is restrained obviously, while the trapped B-DWs is affected slightly. These phenomena indicate that we can obtain a smoother and broader SC or blue-extended SC just by choosing appropriate SS coefficients.



## 1. Introduction

Since its first observation by Ranka et al. in 2000 [1], supercontinuum generation (SCG) in photonic crystal fibers (PCFs) has been remained a subject of extensive research [2]. This striking discovery has wide applications in metrology [3], spectroscopy [4], and microscopy [5]. When a PCF is pumped by a femtosecond laser pulse in the anomalous dispersion regime [6], the Raman scattering and high-order dispersion are the two primary factors that affect the ideal periodic high-order soliton evolution [7–10]. Consequently, the high-order soliton temporally breaks up and is transformed into its constituent red-shifted fundamental soliton components. The process is called soliton fission [9,11]. During such a process, dispersive wave (DW) is emitted due to the energy transfer from soliton to narrow-band resonance in the normal dispersion regime [11,12]. The wavelength of the so-called DW can be either red- or blue-shifted with respect to the central wavelength of soliton, depending on the phase-matching condition between the DWs and the solitons [7,13,14]. The red-shifted solitons will ultimately impose a trapping potential on the DWs via group-velocity matching (GVM) and cause them to continuously blueshift while being group-velocity-matched [11,13,15]. Judge et al. showed that a changing group velocity in a nonuniform fiber lead to the same trapping mechanism as for a decelerating Raman soliton in a PCF [16]. The interaction between solitons and coexisting DWs turns out to be an interesting topic and it has been studied extensively over at least two decades [16]. More recently, the interaction of a normally dispersive wavepacket with a Raman soliton has been given a firm theoretical basis [17,18].

Recently, there has been renewed interest in the process of soliton trapping. Soliton trapping in optical fibers was theoretically discussed by Menyuk [19]. Sørensen et al., demenstrated how the gradient of the tapering in a fiber can significantly affect the soliton trapping and DWs [20]. In conventional fibers, only blue-shifted dispersive waves (B-DWs) can be observed because the dispersion slope is always positive for commonly used frequency. Therefore, a large number of investigations are generally about B-DWs trapped by solitons in fibers which have just one zero-dispersion wavelength (ZDW) [21]. However, the flexible design freedom of PCFs makes it possible to fabricate PCF with two ZDWs within the spectrum, and so we can obtain a negative value of dispersion slope in PCFs with two ZDWs if the pump wavelength is near the second ZDW. Therefore, the PCFs provide an opportunity for observing the red-shifted dispersive waves (R-DWs) [13]. It's encouraging to observe both B-DWs and R-DWs simultaneously. In Ref. [13], the mechanism of soliton trapping of DWs in PCF with two ZDWs is disclosed. The roles of chirp on soliton trapping of DWs in PCF with two ZDWs are unfolded in Ref. [22]. In addition, the generation of DWs in the SCG process in PCFs is explored under different conditions [23]. The roles of high-order dispersion and different dispersion slopes in the generation and control of DWs are illustrated [24,25]. The effect of anomalous SS on DWs generation in metamaterials is clarified [26]. In Ref. [20], it shows that the efficiency of the soliton trapping can be affected by the

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http://dx.doi.org/10.1016/j.optcom.2015.09.013

group-acceleration mismatch (GAM). Sørensen, et al., further verified experimentally the importance of the GAM on solitonic dynamics and the efficiency of SCG [27]. They also demonstrated that a higher power in the blue edge of the spectrum will be yielded due to a correspondingly lower GAM [20,27]. Based on these theoretical works, we qualitatively discuss the impact of SS effect on soliton trapping of DWs. New features are revealed when a femtosecond pulse is launched in the anomalous dispersion regime. It's encouraging to observe the impacts of SS effect on soliton trapping of B-DWs and R-DWs simultaneously, a situation which is not explored previously.

Steffensen et al., developed an analytical model for Raman soliton-frequency shifting (SSFS), which includes the SS term, second- and third-order dispersion, the full Raman term, and the effect of two-photon absorption [28]. In our simulation, we find that the SS effect plays a key role in the suppression of SSFS, which leads to the GVM condition is more difficult to be satisfied, and ultimately results in the energy redistribution between red-shift solitons and DWs [15,29]. As a result, the intensity of trapped B-DWs and R-DWs can be influenced simultaneously. In this paper, we show that soliton trapping of DWs can be affected by the SS effect.

## 2. Numerical model

For the numerical model of the nonlinear pulse propagation in the PCF, to define the SS term clearly, a well-known normalized generalized nonlinear Schrödinger equation (GNLSE) is used to better present a numerical investigation of the self-steepening effect:

$$\frac{\partial U}{\partial z} = \sum_{k\geq 2} \frac{i^{k+1}\beta_k}{k! T_0^{\,k}} \frac{\partial^k U}{\partial \tau^k} + i\gamma P_0 \left[ |U|^2 U + is\frac{\partial}{\partial \tau}(|U|^2 U) - \tau_R U \frac{\partial |U|^2}{\partial \tau} \right] \quad (1)$$

We introduce a normalized amplitude $U$ and a time scale normalized to the input pulse width $T_0$

as: $\tau = T/T_0 = (t - z/v_g)/T_0$, $T$ is measured in a frame of reference moving with the pulse at the group velocity $v_g$, $z$ is the longitudinal coordinate along the fiber axis, $\gamma$ is the nonlinear parameter of the fiber, $P_0$ is the peak power, and $\beta_k$ is the $k$th-order dispersion coefficient at the central frequency $\omega_0$. Dispersion effects are described by the first term on the right hand side of Eq. (1), whereas nonlinear optical effects such as self-phase modulation (SPM), stimulated Raman scattering, and SS effect correspond to the second one. The dispersion parameters $\beta_k$ is a polynomial fit of order 15 to reach a good interpolation of the dispersion profile of PCF with two ZDWs. To gain a physical understanding of the effects, the fiber loss $\alpha$ is neglected since only short length of the fiber is considered in the simulation. We adopt the unchirped hyperbolic-secant pulses in the numerical simulation, $A(0, T) = \sqrt{P_0}\,\mathrm{sech}(T/T_0)$ where $T_0$ is related to the the full width at half maximum (FWHM) of the input pulse width by $T_{FWHM} \approx 1.763T_0$ [14], and we introduce a normalized amplitude $U$ as: $A(z, T) = \sqrt{P_0}U(z, T)$, the self-steepening parameter $s$ is: $s = 1/(\omega_0 T_0)$ [7,9,30]. $E_0 = 2P_0T_0$ is the input pulse energy. Eq. (1) is solved numerically by the standard split-step Fourier method.

## 3. Numerical results and discussions

In this paper, the nonlinear parameter for the fiber is $\gamma = 0.410\ \mathrm{W}^{-1}\,\mathrm{m}^{-1}$, the fiber loss is $\alpha = 0$.

The fractional contribution of the Raman response is $f_R$, typically taken as $f_R = 0.18$ in PCF. The dispersion profile and relative group delay as a function of the wavelength for the fiber used here

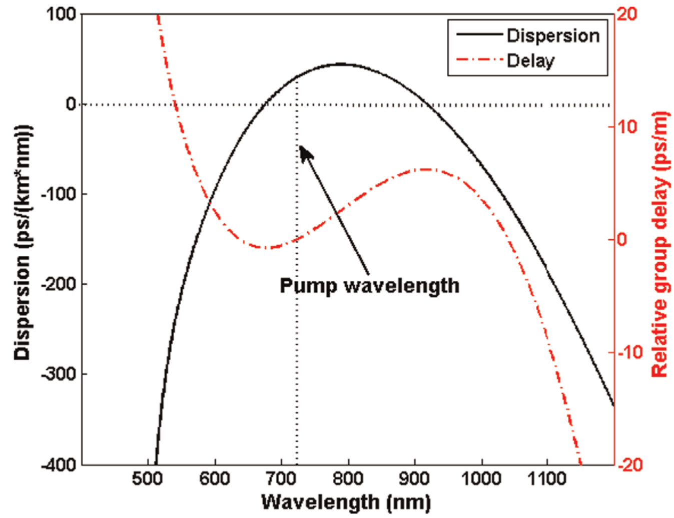


**Fig. 1.** Dispersion profile (black solid curve) and relative group delay (red dashed curve). as a function of the wavelength for the PCF. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

are presented in Fig. 1. The fiber we used is a PCF, which exhibits two ZDWs. The two ZDWs are located in 655 nm and 930 nm and provides a dispersion profile with both positive and negative dispersion slopes [13]. The dispersion between the two ZDWs is anomalous and outside the region is normal. Here, the parameters of input pulse in our numerical simulation are as follows: the pump wavelength $\lambda_0 = 725$ nm, the fiber length is 60 cm, and maintain the peak power at 200 W.

We adjust SS coefficient by simply changing the initial pulse width to proceed our analysis, but the carrier frequency $\omega_0$ is fixed to ensure that the dispersion parameter $\beta_k$ remains the same. It also should be noted that the spectral width of the input pulse satisfies the condition $\Delta\omega << \omega_0$ when changing the initial pulse width in our numerical simulations, so Eq. (1) is always applicable.

Provided a large spectral overlap exists, the pump efficiently sheds away energy to DWs which fall in the normal dispersion regime of the PCF. The center frequencies of DWs are determined by the phase-matching condition [7,13]:

$$\Delta\beta = \beta(\omega_p) - \beta(\omega_{DW}) = (1 - f_R)\gamma(\omega_p)P_p - \sum_{n\geq 2}^{n=15} \frac{(\omega_{DW} - \omega_p)^n}{n!}\beta_n(\omega_p) = 0 \quad (2)$$

where $\beta(\omega_p)$ and $\beta(\omega_{DW})$ represent the propagation constants at the angular frequency of the pump $\omega_p$ and the dispersive wave $\omega_{DW}$, respectively. Here, $\gamma$ is the nonlinear coefficient of the PCF and $\beta_n(\omega_p)$ denotes the high-order dispersion. The factor $f_R$ accounts for the fractional contribution of the Raman delayed response of the fiber and $P_p$ is the peak power of the pump. For soliton propagating in the anomalous dispersion regime, if $\beta_3 > 0$, the DW is generated in the blue side and it travels slower than the Raman soliton. Exact opposite happens for $\beta_3 < 0$, that is, the DW is generated in the red side and travels faster than the Raman soliton. The dispersion slope in the vicinity of the second ZDW is negative, whereas it is positive near the first ZDW.

To fully understand the role of SS effect in the DWs generation and soliton trapping of DWs, we first present the spectral evolution of the input pulses with different SS coefficient propagating in the 60 cm PCF, as shown in Fig. 2. The spectral intensity using a logarithmic density scale is truncated at −50 dB with respect to the maximum value. In the frequency domain, the spectrum broadening is initiated by SPM, as the injected pulse attains its maximum bandwidth after strong temporal compression, high-order soliton breaks up into its fundamental solitons due to