Effect of zero-nonlinearity point on optical event horizon in defocused nonlinear media

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Abstract

We numerically show that a pump pulse close to the zero dispersion wavelength on the anomalous dispersion side in a self-defocusing (negative) nonlinear medium can excite resonant radiation due to shock wave formation. This shock wave is responsible for pulse splitting, and subsequently blue solitons are generated when the leading edge of pump pulse hits the zero dispersion wavelength. The interaction of this soliton with one of the pulse component (interpreted as control pulse) generates a reflected wave upon collision, which may be viewed as an optical event horizon like situation. The collision length is controlled by the zero nonlinearity wavelength (the wavelength at which the nonlinear index coefficient, n_2 becomes zero) of silver nanoparticle doped photonic crystal fiber. Interaction of control pulses with solitonic pulse modifies the trajectory of the soliton.

1. Introduction

Solitary waves have been the subject of intense research in many different fields like hydrodynamics and nonlinear optics [1-2]. Dispersive waves (DWs) form easily when solitons are excited close to the zero dispersion wavelength (ZDW). Depending on phase matching conditions, DWs are radiated at some specific frequency across the zero dispersion wavelength [1, 3].

Fiber optical analogue of event horizon can be realized when a weak pulse interacts with a solitary pulse [4-6] in a positive Kerr nonlinear medium. Collisions between solitons with dispersive waves or between solitons alter the soliton trajectory in frequency and time domain during propagation [7]. Based on two pulse collision compressible octave spanning supercontinuum generation is found in [8] which neither incorporates soliton fission nor modulation instability. Here the phenomenon of event horizon is mimicked in negative nonlinear medium. Negative nonlinearity can be observed by the utilization of composites containing metal nano-particles (NPs) [9]. Using this concept in [10] propagation of femtosecond pulses in presence of zero dispersion wavelength (ZDW) and zero nonlinearity wavelength (ZNW) is investigated and found a number of unique features such as restriction of Raman red shift. In this work femtosecond pulse excites in non-solitonic domain, forms a shock mediated soliton, interacts with the control pulse (CP) develops an optical event horizon like situation in silver NP doped fiber. We show how the ZNW regulates the position of event horizon.

2. Modified GNLSE in composite waveguide

In this work, we consider a solid core photonic crystal fiber (PCF) doped with silver NPs in silica host glass as shown in the inset of Fig. 1. It contains hexagonal array of circular air holes around the core which is silver NP doped silica glass. Parameters for the silver NP doped PCF like pitch (^ distance between two air holes), core diameter and filling factor (f) [11] of metal (NPs) are 1.7 μm , 2.5 μm and 1.3×10^{-2} respectively. The typical dispersion and nonlinear profile of the proposed fiber is shown in Fig 1.

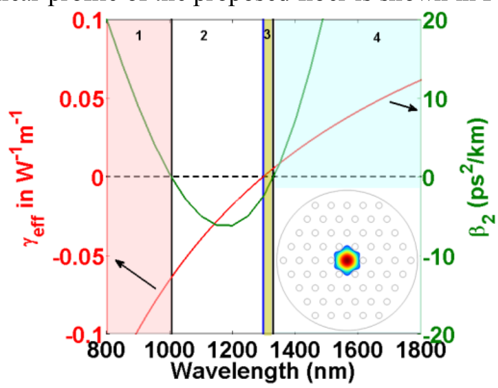

Figure 1. Dispersion and nonlinear profile of doped PCF. Fiber structure along with fundamental mode at 1060 nm is shown at the inset.

We have modified the generalized nonlinear Schrödinger equation (GNLSE) in the retarded time $T = t - \frac{z}{V_g}$ frame travelling at the group velocity, assuming the slowly varying envelope approximation $A(Z,T)$ at the operating frequency ω_0 [1,10]

$$\begin{aligned} & i\partial_Z A + d_T(\partial_T)A + \gamma_{eff}|A|^2 A \\ & + f_R \gamma A \int_{-\infty}^{T} h_R\,(T-T')|A(z,T)|^2 dT' \ = 0 \end{aligned} \quad (1)$$

Operator $d_T(\partial_T) = \sum_{n>1} \beta_n\,(i\partial_T)^n/n!$ represents dispersion operator, γ_{eff} is frequency dependent nonlinear coefficient modified due to metal NPs [10]. γ is the nonlinear coefficient for the undoped PCF.

3. Results and discussions

A sech-pulse of 50 fs is launched at 1060 nm with peak power of 1 kW close to the first ZDW (1006 nm). The launching regime is non-solitonic ($\beta_2\gamma_{eff} > 0$) in nature and because of that, pulse spectrum initially broadens due to SPM followed by optical wave-breaking. Here the pump pulse will encounter four different spectral regions as shown in figure 1. Region 1 and 3 are solitonic ($\beta_2\gamma_{eff} < 0$) and region 2 and 4 are non-solitonic in nature. Blue and red components of the pulse initially experience opposite types of group velocity dispersion (GVD) with defocusing nonlinearity. Blue component of the pulse, experiences normal GVD with negative Kerr nonlinearity forms a shock wave mediated soliton. So spectrum at 40 cm develops an asymmetric broadening towards the blue side due to first ZDW shown in figure 2.

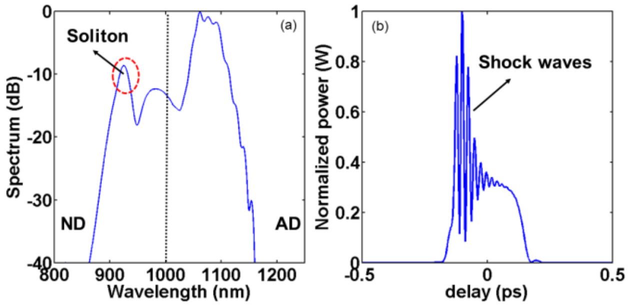

Figure 2. Spectral output at 40 cm showing shock assisted soliton. Black vertical dotted line indicates first ZDW at 1006 nm bifurcating normal dispersion (ND) and anomalous dispersion (AD) regime. (b) Temporal output showing shock waves phenomenon at same length.

Now in order to understand the physics in detail we have plotted density plots as shown in figure. 3 (a) and (b). Due to third order dispersion soliton resonates to give radiation around 1200 nm. This radiation is often referred to as resonant radiation (RR) induced by shock waves; it is indicated in fig. 3. By virtue of second ZDW around 1330 nm, a red DW around 1700 nm is generated. Now the fascinating part is the unusual trajectory of this blue soliton shown in fig. 3 (b). This soliton bends at two different propagation distances. The first bending occurs due to intra-pulse Raman scattering (IPRS)-induced red shift of the soliton. This frequency downshifting is eventually suppressed as it approaches the first zero dispersion point, and bends subsequently as it propagates. As a result of group velocity dispersion, one of the pulse components in anomalous dispersion (AD) regime approaches the solitonic pulse (SP) and traps that component. The cross-phase modulation (XPM) interaction develops which shifts the soliton spectrum little towards red side and trapped non-solitonic spectrum towards blue. This is illustrated as the spectral attraction in the spectrogram in fig. 4 (a). Now this trapped pulse is designated as control pulse (CP), which is reflected from SP due to substantial refractive index change from the nonlinear interaction between weak CP and strong SP. This nonlinear interaction is interpreted as optical event horizon (EH) as the CP is unable to pass through SP during collision. Collision increases the group velocity of both the CP and SP [fig. 3 (b)]. As SP is greatly affected by virtue of reflection it therefore drifts in opposite direction after propagating a distance of 4.2 m. The drift of SP trajectory with large group velocity is a consequence of EH. Now this EH can be controlled by ZNW. Energy transfer occurs due to the nonlinear interaction, as is clearly visualized in spectrogram at 7 m fiber length [fig. 4 (b)].

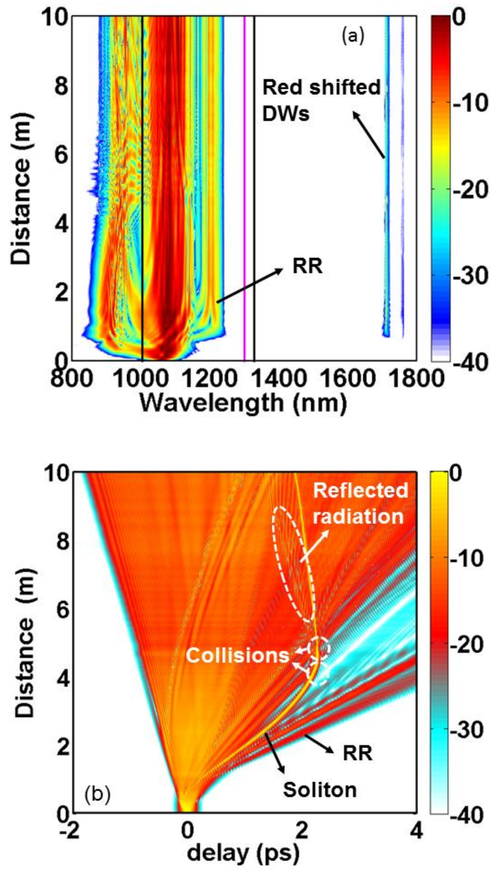

Figure 3. (a) Spectral density plot. Two black vertical lines indicates two ZDW (1006 nm and 1330 nm) and red vertical line indicates ZNW (1299 nm). (b) Temporal density plot indicating collisions and reflected radiation.

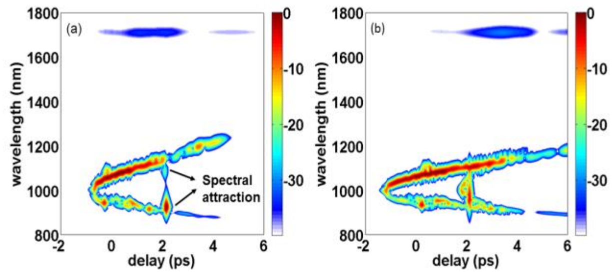

Figure 4. (a) Spectrogram at 4 m length indicating the spectral attraction. (b) Spectrogram at 7 m showing energy transfer.

When comparing the solitons between fig. 4 (a) and 4 (b), we observe that SP in fig. 4 (b) is more compressed in time domain with broader spectrum compared to fig. 4 (a). This signifies that the soliton is encountering different GVD after collision. Similar phenomenon is found in dispersion decreasing fiber where the soliton adiabatically compresses due to change of GVD [1]. Therefore we may conclude that the collision between SP and CP leads to GVD change of SP.

Now the entire pulse dynamics is studied by increasing the nonlinear dispersion or by changing ZNW from 1299 to 1252 nm. In this case, shock mediated effects occur at slightly lesser distance. So SP starts to bend slightly (first bending) at earlier distance. It is known from [10] that ZNW acts as a barrier for SP. So by increasing the nonlinear dispersion, the barrier effect will be shifted by the SP to shorter distance. Here we observed the reflected radiation at 3.6 m compared to 4.2 m as in previous case. In other words, the event horizon can be controlled by shifting ZNW. The ZNW can be controlled by changing f of metal nanoparticles [10]. Now to elucidate the effect of the ZNW on the event horizon, we plot the delay curve of SP in Fig. 6 (a) with propagation distance by varying nonlinear dispersion (γ_{1eff}). The latter effect can be incorporated in Eq. (1) as $\gamma_{eff}(\omega) \approx \gamma_{0eff}(\omega_0) + \gamma_{1eff}(\omega - \omega_0)$. Finally, in Fig. 5 (b) we plot the distance at which event horizon occurs with ZNW, with a cubic dependence.

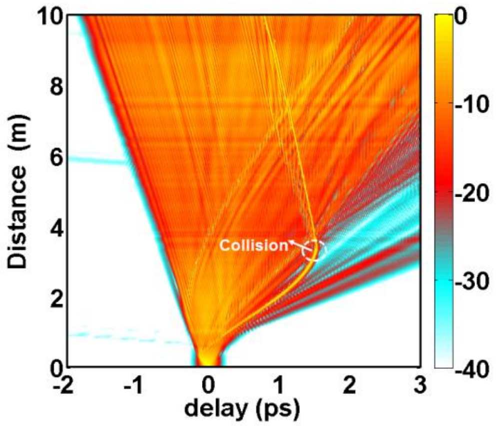

Figure 5. Temporal evolution showing collision at 3.6 m.

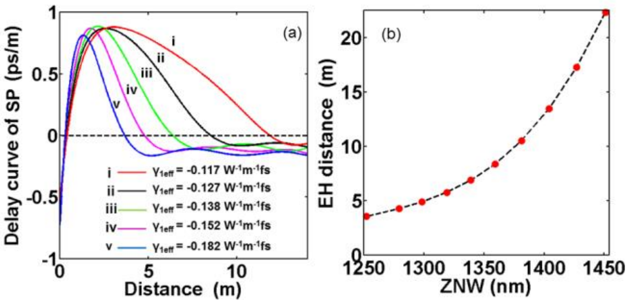

Figure 6. (a) Delay curve of Raman soliton for various nonlinear dispersion. Second cutting point indicates distance at which EH starts. (b) Variation of 2nd zero cutting point in (a) or the EH distance with ZNW (red dots). The dashed line is a cubic polynomial fit of the data.

5. Conclusions

We studied numerically the propagation of femtosecond pulse inside the doped PCF, which generates shock assisted soliton and RR during propagation. We show that the scattering of CP at an optical event horizon modifies the trajectory of SP. In particular we have seen how the ZNW controls the collision region or tuning the position of the event horizon.

6. Acknowledgements

The authors acknowledge G. P. Agrawal and G. Steinmeyer for stimulating discussions. This work is supported by CSIR 12th plan GLASSFIB Project No. ESC0202. The author RC and SKB thankful to CSIR-ES scheme-21(2017)/15/EMR-II.

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