Asian Journal of Physics
Vol. 28, Nos 7-9 (2019) 541-552
Available on: www.asianjournalofphysics.in

Towards stable delivery of high energy through background-guided similariton pulses

Piyali Biswas and Somnath Ghosh
Department of Physics
Indian Institute of Technology Jodhpur-342 037, Rajasthan, India

Invited Article dedicated to Prof Ajoy Ghatak on his 80th Birthday

Stable delivery of high energy optical pulses through fibers is an attractive field of research owing to its wide applications in defense, bio-medical industry, chemical industry and so on. Delivery of such high energy can be possible by exploring the inherent potential of background-guided parabolic optical pulses. Asymptotic evolution of parabolic pulses largely depends on the initial pulse energy fed at the input of the fiber. Here, we have investigated the effect of presence of a hyperbolic tangent pulse as the background of an input Gaussian pulse. Further, we have numerically demonstrated the stable propagation of the evolved parabolic pulse with its characteristic linear chirp. A background-guided Gaussian pulse and a background-guided hyperbolic secant pulse, centered at 980 nm wavelength, have been fed at the input end of a dispersion decreasing Bragg fiber and allowed to propagate over several kilometers of the fiber length. The entire propagation has come out to be more stable, and shows closer asymptotic behavior in comparison with the conventional propagation of a single Gaussian or a single hyperbolic secant pulse of same energy. Such a scheme should be attractive in stable delivery of high energy pulses including applications in mid-IR spectroscopy, defense and medical surgery.

Keywords: Parabolic pulse, Nonlinear fiber optics, High energy pulse, Similaritons.

1 Introduction

Lately, high-energy laser sources have witnessed a significant demand in the chemical industry, and bio-medical industry other than the exclusive applications in defence. Such wide range of applications eventually require compact, robust and easy-to-implement high energy all-fiber systems/devices that will deliver stable and self-consistent high energy optical pulses. However, such high energy pulses undergo wave-breaking due to the onset of strong nonlinear interactions during their propagation through fibers which, limits their utility in such all-fiber systems [1]. Earlier it was really difficult to send high power short pulses through a very long fiber length due to wave-breaking through nonlinear optical effects until a group of researchers discovered that this limitation can be overcome by transmitting certain wave-breaking-free pulse shapes through appropriate fiber design (s) [2].The first theoretical and experimental evidence of the propagation of such breaking free pulses have been reported in [3] wherein an input pulse would be reshaped into parabolic shape in their time-domain profiles [3]. Such parabolic pulses can suppress wave-breaking due to the development of monotonically varying (mostly linear) frequency chirp which gradually preserves the parabolic shape irrespective of its expansion or compression during their propagation [2]. Unlike Soliton, such pulses preserve their shape by scaling of their amplitude and temporal-width leading to a self-similar evolution for which they are known as *Similariton*. In this context, we should note that there are two fundamental approaches to the solution of the nonlinear Schrödinger equation (NLSE) with normal disperion which governs all possible dynamics of pulse propagation. One approach leads to the solution of

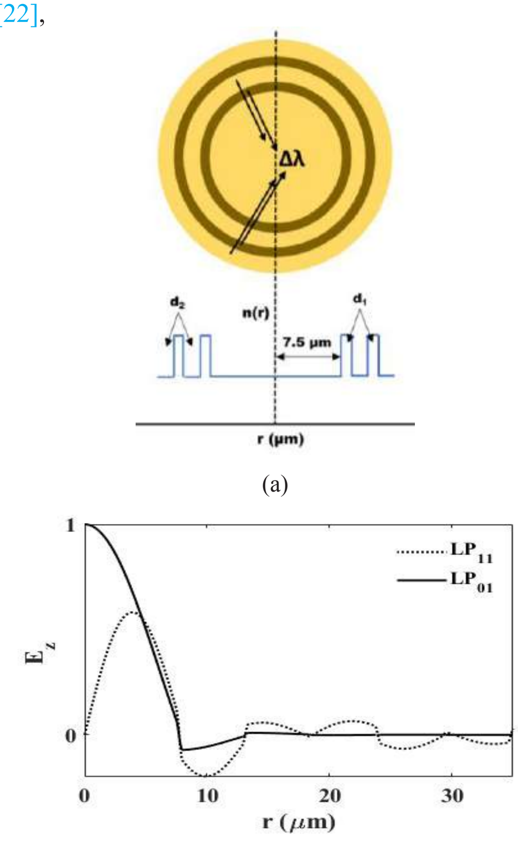
Corresponding author :
e-mail: somiit@rediffmail.com (Somnath Ghosh)

the nonautonomous NLSE with varying coefficients. It gives us an exact solution in the form of hyperbolic secant (*sech*; bright similaritons) and hyperbolic tangent (*tanh*; dark similaritons) functions embedded in infinite background, and these are hard to obtain as they need delicate balance between fiber parameters such as dispersion, nonlinearity and gain-loss [4-7]. The other approach results in asymptotic solution of autonomous NLSE in presence of amplification and spatial inhomogeneity. The realization of this scheme is comparatively straight forward [3,8]. In fiber amplifiers, such asymptotic solutions of NLSE with gain and normal dispersion leads to evolution of parabolic pulses with linear chirp from any input seed pulse and the evolution depends on the input pulse energy rather than its specific shape. A number of reports have successfully demonstrated parabolic pulse generation and its self-similar propagation through gain-assisted fibers [3,8]. In 2000, Fermann *et al* reported the first experimental realization of linearly chirped parabolic pulses through a Yb-doped fiber amplifier [3]. Their report also showed that the formed pulses remain parabolic during their propagation through a standard single mode normally dispersive fiber, thus establishing their self-similar nature. Afterwards, there are successive works on generation of parabolic pulse through Raman fiber amplifier [9], mode-locked lasers [10] and normally dispersive fiber amplifiers [11]. All of these works have eventually confirmed the potential of parabolic pulses to be a stable solution for long range guided-wave propagation. However, formation and stable propagation of such wave-breaking free pulses in passive fibers with no gain is crucial. However, formation and stable propagation of such wave-breaking free pulses in passive fibers with no gain is crucial. In passive fibers, parabolic pulses are formed by tuning the dispersion (normal) of the fiber in such a way that it decreases with propagation along the fiber. Such dispersion decreasing fiber structure and pulse reshaping through it was first reported in 2004 by Hirooka *et al*, which opened up a new avenue of self-similar pulse formation [12]. Though such passive formation through dispersion decreasing fiber is not difficult but its stable propagation over longer distances is a critical aspect due to the development of nonmonotonic frequency chirp during its propagation which ultimately leads to quick deformation of the formed parabolic shape. It is referred to as an intermediate transient state of propagation [13] and is unlike the asymptotic solution as in case of the amplifiers. There are numerous reports on passive formation of parabolic pulses through optical fibers [14-19]. In order to make such propagation stable, various fiber design techniques like dispersion oscillating fiber etc. have been reported where a rapidly varying mean-zero dispersion profile preserves the parabolic pulse over several meter-long fibers [20]. Such oscillating dispersion landscape essentially explores a very small average positive value of dispersion to keep the pulse shape maintained by a smooth roll over from normal to anomalous dispersion regime and vice-versa. However, it is still a challenge to obtain self-similar propagation over very long distances of a dispersion decreasing fiber with comparatively higher dispersion and nonlinearity.

In this paper, we report our detailed and systematic investigation on possible stable delivery of high energy pulses over longer distances to meet the existing technological challenges. Hence, we have studied the asymptotic evolution and stable propagation of parabolic pulses from a background-guided input seed pulse. Even though, the asymptotic evolution is largely dependent on input pulse energy, here we establish that presence of a background pulse will eventually stabilize its propagation over longer distances. For our study, we have chosen a Gaussian seed pulse guided by a hyperbolic-tangent pulse to be propagated through a several-kilometer long dispersion decreasing Bragg fiber (DDBF) at 980 nm wavelength. The propagation of guided-pulse has been compared with the propagation of a single Gaussian input through the same DDBF. Such background guided pulse delivery scheme would find its wide applicability in high energy all-fiber based optical devices for strategic, medical and precision machining applications.

2 Fiber design and numerical model

For the targeted pulse propagation, we have chosen a Bragg type fiber where light is guided by photonic bandgap method. Such fibers can be termed as specialty optical fibers as we can customize the properties of the fiber by suitably designing its transverse cross-section to realize the requirement. It is to be noted that a Bragg type fiber, along with other microstructured fibers, falls under the category of photonic crystal fibers with one-dimensional periodicity [21]. Moreover, the method of light guidance through such fibers is also different from standard step or graded index fibers where light is guided by the core-cladding index difference. The schematic of the Bragg fiber cross-section has been depicted in Fig 1(a) along with the refractive index variation. Unlike a standard step-index fiber (with single cladding layer surrounding the core), such specialty fibers consist of a number of cladding layers with periodically arranged alternate high and low indexed material surrounding a low indexed core (hollow or solid), which form a stop band for the light to be confined in the core. We can obtain a specific band-diagram (frequency vs wave-vector) for a particular cross-section of the designed Bragg fiber. Now in order to confine a particular mode in the core, the frequency and the wave-vector of the mode must lie in one of the bandgaps of the fiber in such a way that it does not leak through the cladding. However, photonic bandgap fibers are leaky structures in a sense that there are always an evanescent field exists in the multilayered cladding. Figure 1(b) shows the mode profiles of the fiber cross-section. The core is specifically designed to host resonances which falls within the stop band of the cladding geometry. If the index contrast is large enough then one can easily employ a simpler asymptotic approximation method for modal analysis. But such approximation method fails when the index contrast is lower and one should explore transfer matrix method with scalar linear polarization (LP) approximation to analyze the modes of the fiber. According to the matrix method technique, modal field distribution will be computed at each cladding interface by expressing the radial part of the field equation under LP approximation as [22],



(b)

Fig 1. (a) Schematic of the Bragg fiber cross-section and the refractive index profile; (b) Field profile of the designed Bragg cross-section; fundamental mode and first higher order modes are shown

$$R(r,z,\theta,t) = [A_j J_l\,(k_j r) + B_j\; Y_l\,(k_j r)]\begin{bmatrix}\cos(l'\theta)\\ \sin(l'\theta)\end{bmatrix}\exp[i(\omega t - \beta z)] \quad (1)$$

with j = 1,2,…….Q and l, l' = 0, 1, 2,…. where, $k_j^2 = n_j^2\left(\frac{\omega^2}{c^2}\right) - \beta^2$. Here, β is the propagation constant, n_j is the j-th layer refractive index, and Q is the total number of cladding layers. Now, at each cladding interface the electric field of the particular mode (characterized by Bessel order l, l') and its derivative should be continuous such that the coefficients (A and B) of the field at one layer is related to the coefficients of the adjacent layer by a 2×2 matrix. For the leaky nature of the Bragg fiber, the coefficients of the incoming component of electric field at the last cladding layer should be zero, i.e. the eigenvalue equation becomes – $E(\beta) = 0$, where β is the propagation constant of the incoming electric field at the last layer. One can easily obtain the effective refractive index and the leakage loss from the plot of $|1/E(\beta)|^2$ vs real (β). The curve shows a Lorentzian peak whose location gives the effective index and full width at half-maxima (FWHM) gives the leakage loss by the relation – Loss (in dB/m) = (k_0×FWHM)/2 , where k_0 is the free space propagation vector. In this context, though such matrix method was actually implemented for analysis of leaky modes in a step index fiber, but it can easily be employed to solid core Bragg fiber structure with low-index contrast without any involvement of solving complex transcendental equations. As the Bragg fibers are less bend sensitive compared with their conventional counterpart, even several kilometers are suitable for the target applications. In our study, the fiber has been designed to be operating at 980 nm wavelength to confine the fundamental mode only. The low indexed core material is LLF1 having refractive index 1.5360 and the cladding is composed of three bi-layers of SF6/LLF1, SF6 being the high indexed material (R.I.=1.7763 at 980 nm). The input cross-section of the fiber is as follows: core radius r = 7.5 µm, high index cladding layer thickness d_1 = 0.5 µm, and low index cladding layer thickness d_2 = 4.9 µm. Such dimensions can be readily obtained by optimizing the cross-sectional parameters using the quarter-wave stack condition for maximum confinement. According to this condition, $d_1 k_1 = d_2 k_2 = \pi/2$, for fundamental mode ($l$ = 0) where $k_{1,2}$ are the corresponding wave-vectors and obtained by the relation - $k_{1,2} = k_0\sqrt{n_{1,2}^2 - n_{eff}^2}$. The fiber design should be such that the leakage losses of higher order modes are readily higher than that of fundamental mode and along with propagation length they die out faster leaving only the fundamental mode confined to the core. For our fiber design, we have considered maximum confinement of the fundamental mode only. For higher order modes where l = 1, the relation becomes, $d_1 k_1 = d_2 k_2 = \pi$ for anti-reflection.

Propagation of optical pulses through optical fibers is governed by nonlinear Schrödinger equation (NLSE). It includes all the dispersion effects through various dispersion coefficients (like group-velocity dispersion, third order dispersion and other higher orders), various nonlinear effects like self-phase modulation, Raman effect, four-wave mixing through various nonlinear parameters and also fiber gain and losses. There are various forms of NLSE among which the standard one will be implemented to study pulse propagation through a dispersion decreasing fiber. Unlike standard step-index fiber, a dispersion decreasing fiber (DDF) is one in which the second order dispersion parameter β_2 varies in such a way that the dispersion is longitudinally reducing. In order to form parabolic pulses through a passive medium based fiber, the fundamental requirement is to have a counterbalanced normal dispersion and nonlinearity that essentially reshapes any standard input pulse shape into parabolic profile during its propagation through the DDF [12]. We consider a slowly varying pulse envelope $A(z, T)$ that is satisfied by any typical optical pulse from commercially available sources, and study its evolution dynamics employing NLSE of the form [23],

$$i\frac{\partial A}{\partial z} + i\frac{\alpha}{2}A - i\frac{\beta_2}{2}D(z)\frac{\partial^2 A}{\partial T^2} + \gamma|A|^2 A = 0 \quad (2)$$

where, α is the loss parameter, γ the nonlinear coefficient giving rise to self-phase modulation (SPM), β_2 is the second order dispersion coefficient at z = 0 and positive (normal dispersion), and $D(z)$ is the length dependent dispersion profile. $D(z)$ is related to β_2 by the relation,

$$D = -\frac{2\pi c}{\lambda^2}\beta_2 \tag{3}$$

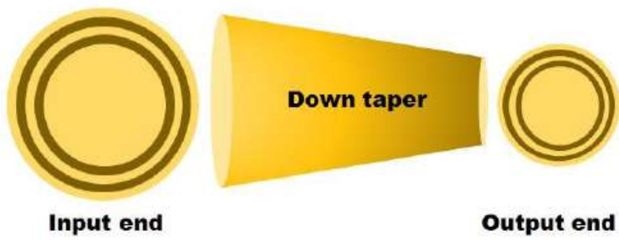
With proper coordinate transformation, Eq (1) has been modified to,

$$i\frac{\partial u}{\partial \xi} - \frac{\beta_2}{2}\frac{\partial^2 u}{\partial t^2} + \gamma|u|^2 u = i\frac{\Gamma(\xi)}{2}u \tag{4}$$

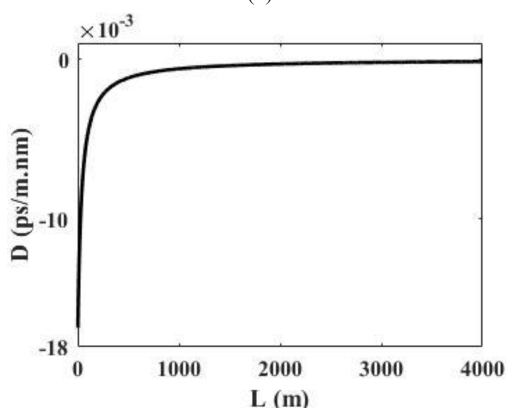
where, $u(\xi,t)$ is the new amplitude as a function of transformed coordinate and $\Gamma(\xi) = -\frac{1}{D}\frac{dD}{d\xi}$ mimics the role of gain in passive fiber giving rise to the asymptotic evolution. For decreasing dispersion profile, it is important to appropriately choose the longitudinal variation $D(z)$. In ref [12], authors showed that $D(z)$ should be a hyperbolic profile, whereas in some articles this variation is an exponential one. For our work we have chosen $D(z)$ to be of the form,

$$D(z) = \frac{D(0)}{1 + \Gamma_0 z} \tag{5}$$

with $D(0) = 1$ at $z = 0$, Γ_0 becomes the effective constant gain. Such a dispersion profile decreases with fiber length z and eventually serves the purpose of equivalent gain in a passive fiber. Here, we have deliberately neglected the higher order dispersion and nonlinear terms for the proposed operating condition. To solve Eq (1) numerically, we have employed Split-step Fourier method (SSFM). SSFM exploits the operator method in which we have two operators - $\widehat{D}$ that accounts for all dispersion and loss terms and acts in frequency domain; $\widehat{N}$ that accounts for the nonlinear terms and acts in time domain. Moreover, the entire fiber length is divided in small length steps dz and both the operators act within dz in an iterative process. This iterative process is indeed faster and accurate in terms of simulation.



(a)



(b)

Fig 2. (a) Schematic of the dispersion decreasing Bragg, whose down-tapering leads to decreasing dispersion; (b) dispersion variation of the designed DDBF

The schematic of the cross-section of the designed Bragg fiber is depicted in Fig 1. At the input cross-section - $D(0) = -17\times10^{-3}$ ps.m^{-1}.nm^{-1}, $\gamma(0) = 1.7\times10^{-3}$ W^{-1}.m^{-1} and $\Gamma_0 = 28\times10^{-3}$ m^{-1}, a constant equivalent to the gain coefficient. The longitudinal fiber profile (down-tapered) has been shown in Fig 2(a). The corresponding dispersion profile has been computed numerically by using Eq (5) and is shown in Fig 2(b). For a Bragg type fiber, the decreasing dispersion profile could be achieved by down-tapering of the fiber. Such fiber tapering is a routine technology today and can be realized using *State-of-the-Art* fabrication techniques with utmost accuracy. The tapering of the fiber means that there will be a fixed ratio of the initial cross-section to the final cross-section either greater than (up-tapering) or less than (down-tapering) unity and the intermediate variation is linear for the simplest case. It is to be noted that the nonlinearity parameter γ has been found to vary a little along the fiber length and considered as nearly constant. Likewise, for the loss parameter α only confinement loss of ~ 10^{-4} dB/m for the fundamental mode have been incorporated. The entire process of Bragg fiber designing has been done numerically by solving relevant field equations in a Matlab® based code.

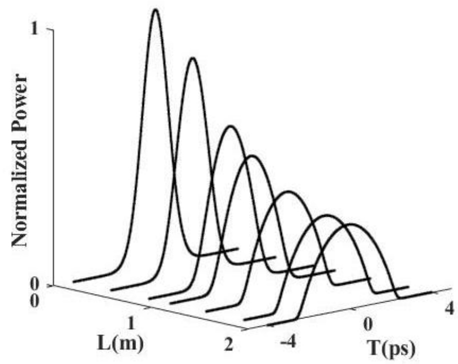
The quality of the formed parabolic pulses has been quantified by computing the mismatch factor between the pulse obtained from simulation, and a fitted parabolic pulse of the same specification. The mismatch parameter M is given by,

$$M^2 = \frac{\int[|u|^2 - |p|2]^2 dt}{\int|u|^4\, dt} \tag{6}$$

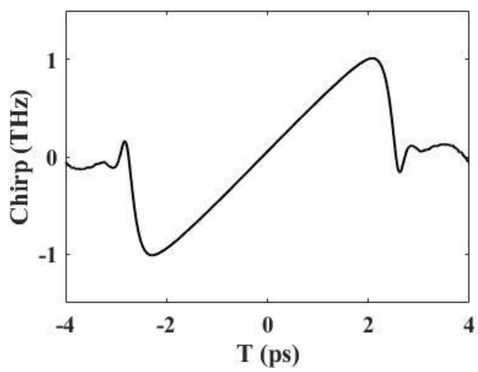
where, p is the fitted parabolic pulse with the same energy as u.

3 Results and discussions

In passive fibers, parabolic pulse formation is driven by the counterbalance of normal GVD and SPM. To understand the evolution, we consider a 2 m long dispersion decreasing fiber with Bragg type cross-section. A unchirped Gaussian pulse of peak power 150 W and full width at half-maxima (FWHM) 2.0 ps is launched at the input end of the 2 m fiber. The evolution of the input pulse is depicted in Fig 3(a). We can observe that gradually over the length of the fiber, the Gaussian profile gets reshaped into a parabolic one. This is quite interesting to realize that in a dispersion varying landscape, the changing dispersion and nonlinearity accumulates the phase in such a way that a Gaussian temporal pulse evolves with propagation to a parabolic form. In Fig 3(b) the variation of the frequency chirp developed during the propagation is shown. It is clearly seen that chirp is linear across the entire pulse width which is its significant characteristic. In order to realize pulse reshaping through the designed DDBF, we have chosen two combinations of composite pulse profiles : (i) a Gaussian input pulse guided by a hyperbolic tangent (*tanh*) pulse and, (ii) a hyperbolic secant pulse (*sech*) guided by the *tanh* pulse, and compared the stability of the propagation. Moreover, the input parameters for Gaussian and *sech* pulses have been kept same as peak power = 100 W and FWHM = 3.0 ps. The *tanh* input parameters are chosen to be - peak power = 100 W and FWHM = 0.3 ps. We have studied in-depth the evolution of the two pulse combinations through our designed DDBF. The temporal profile of the input pulses (normalized) have been depicted in Fig 4(a) and 4(b) where the peak values are less than unity due to the presence of the *tanh* pulse at the center. One should note that if the power of the *tanh* background is reduced, then the depth of the dip will automatically be decreased by rasing the peak values of the input pulse. Such background guided pulses have been allowed to propagate over several kilometers of the same DDBF and the output pulse profiles and developed frequency chirps are observed at the end of 4 km. The temporal profiles of the output pulses are depicted in Fig 4(c) and 4(d) in which we observe a significant change in pulse profiles. For both the input combinations, the output is parabolic in shape. However, the normalized peak power has reduced as it has undergone significant broadening in width (output FWHM ~ 20 ps). Such large broadening is due to a large accumulation of dispersion and nonlinear phase shift. During the pulse evolution, the pulse width is widened; the power profile is also being adjusted in such a way that the parabolic shape is maintained throughout. This dynamics approaches the self-similar evolution. We can observe such self-similar evolution effect for both the dual-pulse but the stabilities differ.



(a)



(b)

Fig 3. (a) Evolution of an input Gaussian pulse to parabolic pulse after propagating 2m through a tapered fiber; (b) frequency chirp variation with time developed during the propagation of the unchirped Gaussian pulse

It is clear from the Fig 4(c) that the output is smoother up to 4 km of the DDBF length, whereas Fig 4(d) shows some distortions in the output pulse profile which indicates that the pulse has entered the wave-breaking regime. Figure 4(e) and 4(f) are the logarithmic plots of the output pulse profiles. The top hat profile is the signature of the temporal parabolic shape at the output. The presence of the central dip is due to the *tanh* pulse which can be controlled by tuning the power and width of the guiding background. Both the output profiles are clearly showing a difference between the two evolutions. The *tanh*-guided *sech* input has evolved to a parabolic profile (characterized by the top hat log plot) but with certain oscillations at its edges which indicate a clear limitation of its maximum stable propagation length and its asymptotic evolution. On the other hand, the evolution of the *tanh*-guided Gaussian pulse through the DDBF has been stable and smooth indicating its potential for long-distance stable propagation. Moreover, the developed frequency chirp for both the pulse combinations are linear across the entire pulse width having a small kink at the position of the central dip shown in Fig 4(g) and 4(h). Here, also we can observe that the chirp profile for the *tanh*-guided Gaussian pulse is smooth and linear than that of the *tanh*-guided *sech* pulse. For the second case we observe small oscillations at the same time-scale where ripples in temporal profile has occurred, which eventually reassures the wave-breaking. Such nonmonotonic nature of the chirp for *tanh*-guided *sech* pulse is a clear indication that with further propagation it will undergo complete wave-breaking. Comparatively, the monotonic chirp of the *tanh*-guided Gaussian pulse is a better combination that could survive over several kilometers self-similarly through the DDBF.

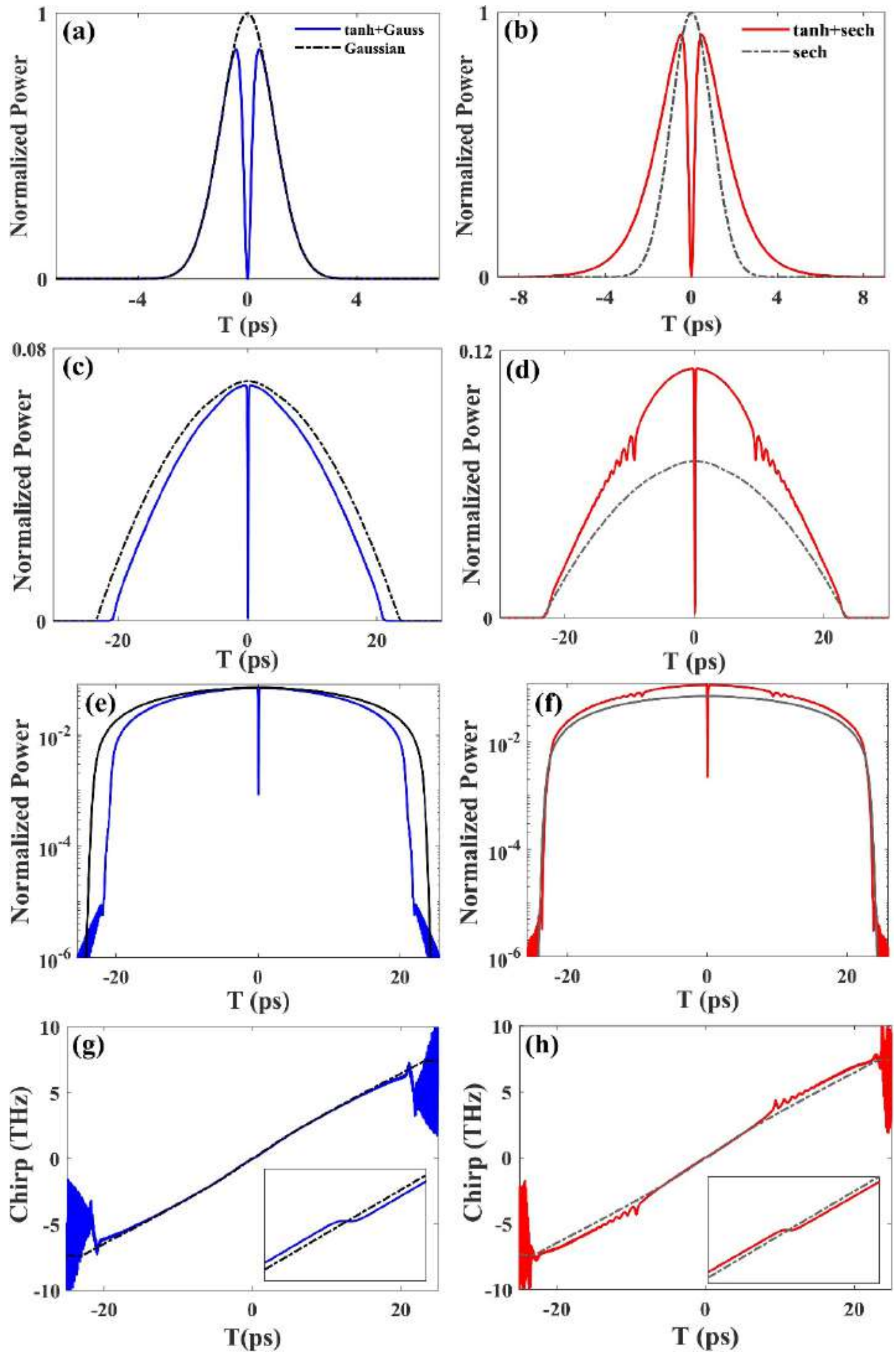


Fig 4. (a) The input power profiles of a single Gaussian and a *tanh*-guided Gaussian pulse; (b) The input power profiles of a single *sech* and a *tanh*-guided *sech* pulse; (c) The output power profiles obtained from a single Gaussian and *tanh*-guided Gaussian pulse; (d) The output power profiles obtained from a single *sech* and *tanh*-guided *sech* pulse; The logarithmic plot of (c) and (d) are shown in (e) and (f), respectively. The corresponding frequency chirp variations are shown in (g) and (h), respectively

For a better understanding of the effect of via a background pulse, we have compared these results with the observations made from the propagation of a single Gaussian pulse and a single *sech* pulse of same power and FWHM through the designed DDBF. Figure 4(a) and 4(b) depict the single Gaussian and *sech* inputs of peak power = 100 W and FWHM = 3.0 ps which has been allowed to propagate through the DDBF over 4 km and the output pulse profile (both linear and log plot) has been captured at the end of 4 km shown in Fig 4(c) – 4(f). Again, the top hat profile shows that the output is a parabolic pulse with a clean linear chirp depicted in Fig 4(g) and 4(h).

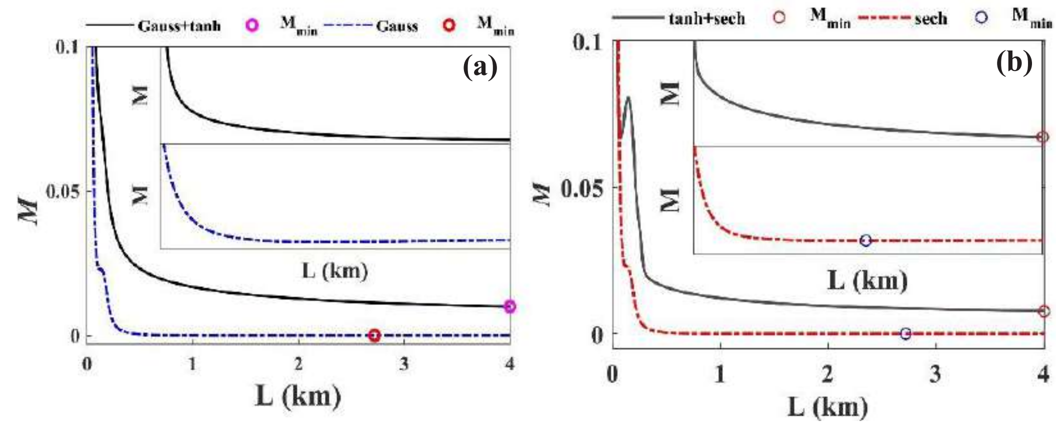


Fig 5. The evolution of the misfit parameter *M* through the designed DDBF for (a) a single Gaussian and a *tanh*-guided Gaussian pulse, and (b) a single *sech* and a *tanh*-guided *sech* pulse. The locations marked by the colored circles are the points where we have obtained minimum misfit M_{min}.

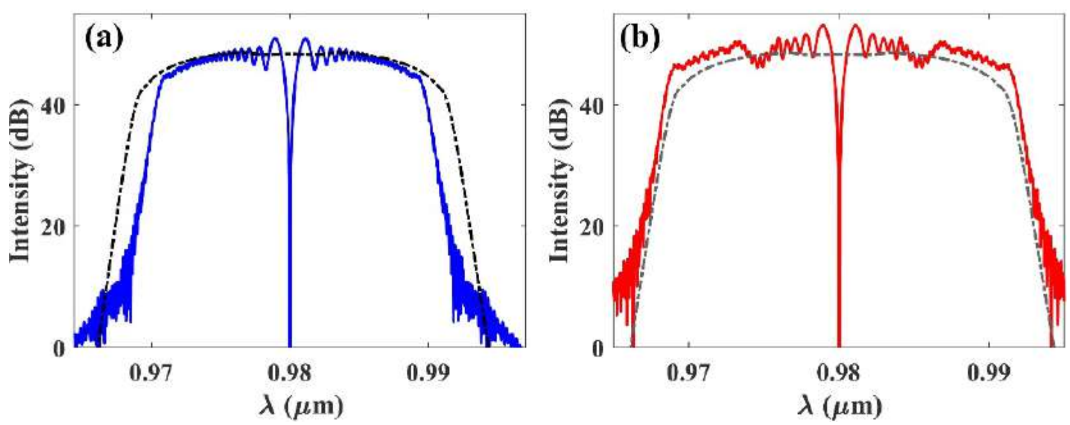


Fig 6. The output spectra obtained from (a) a single Gaussian (black dashed curve) and a *tanh*-guided Gaussian pulse (blue curve), and (b) a single *sech* (grey dashed curve) and a *tanh*-guided *sech* pulse (red curve).

From the observations made so far, it is established that presence of *tanh* pulse at the background of both the Gaussian and *sech* pulses help in retaining the pulse reshaping through the DDBF and it evolves smoothly with the main seed pulse without any further significant evolution of its own. To understand the impact of its presence on propagation, we have plotted the evolution of the misfit parameter *M* as a function of fiber length *L* for all four types of input pulses – two combination of pulses and two single pulses. From Fig 5(a) it is clear that the reshaping of single Gaussian to parabolic is faster than the *tanh* guided Gaussian and also it reaches a minimum of 10^{-4} around 2.5 km of fiber length. However, it starts to rise again with further propagation, gradually revealing the intermediate transient state (shown as inset in Fig 5(a)) reported earlier in case of passive reshaping. Whereas, the *tanh* guided pulse slowly evolves into parabolic, reaches a minimum of 10^{-3} at around 4 km and on further propagation it keeps on decreasing *showing asymptotic nature of pulse evolution* (inset of Fig 5(a)). Similarly, Fig 5(b) depicts the faster evolution of single *sech* pulse than the dual-pulse. We can observe that *tanh* guided *sech* pulse has an initial distortion at near 100 m but it gradually comes down and matches the parabolic profile with further propagation. In this case also, we have obtained an asymptotic nature of evolution for *tanh*+*sech* pulse with gradual fall down of *M* (shown as inset of Fig 5(b)), whereas single *sech* pulse starts rising up after certain length of the DDBF. Thus, the presence of *tanh* pulse at the background *actually stabilizing the pulse propagation and gives a robust parabolic pulse with linear chirp at the end of a passive fiber*. The stability of the pulse may depend on the input energy of the pulse which may be investigated in depth.

Moreover, the respective output spectra have been depicted in Fig 6(a) and 6(b). The output spectrum of the single Gaussian pulse has a smooth flat top, and so the case of a single *sech* pulse, whereas the *tanh* guided pulse is showing small oscillations at its output. Such spectrum is distorted in case of *tanh*+*sech* pulse where the oscillations at the top are unequal and random. On further tuning of such comb-like spectral profile of the background guided Gaussian pulse, it should be useful for applications like comb-spectroscopy.

From application point of view, such background guided pulse propagation is of immense importance for long distance distortion-free high-power pulse delivery. From the results of Fig 5, we can eventually conclude that a *tanh* guided Gaussian pulse would carry more energy over longer distances than its single Gaussian counterpart. The striking result of this investigation is that the evolution of pulses nearly asymptotic in a passive fiber that matches the evolution of parabolic pulses in amplifiers mitigating the issues related to amplifier-based pulse formation. Moreover, its self-similar nature of propagation is maintained, thus resulting in no or little further temporal distortion which makes it suitable for long distance delivery. For high energy applications like precision machining [24], bio-medical imaging [25], laser-launched detonation processes [26] where very high energy (~ several mJ) optical pulses have to be delivered over distances from several meters to few kilometers, such background guided pulse will undoubtedly meet the requirement for its robust nature. Furthermore, the comb like output spectrum corresponding to the *tanh* guided pulse should be very interesting for more in-depth study because of its potential applications in all-fiber based comb spectroscopy [27].

4 Conclusion

In summary, we have investigated the robustness of a parabolic pulse through longer propagation distances by exploring the evolution of a Gaussian input pulse and a hyperbolic secant pulse guided by a hyperbolic tangent pulse at its center. For this, we have designed a Bragg fiber with longitudinally decreasing dispersion profile. At the end of 4 km of the DDBF we have obtained a parabolic pulse with an intensity dip which evolves asymptotically with propagation through the designed fiber. For comparison, a single Gaussian pulse and a single *sech* pulse of same input parameters have been allowed to propagate through the same DDBF which leads to an intermediate transient state of evolution. Such findings should be of interest in further development of passive pulse reshaping and would eventually open up new routes to deliver stable high-energy pulses in all-fiber device applications such as strategic applications, medical and industrial machining.

Acknowledgement

One of the authors (SG) had the privilege of working with Prof Ajoy Ghtak during his first research project at IIT Delhi. Prof Ghatak has been a guide, mentor and source of inspiration for me over the last 12 years. His contribution to optics research and teaching in India is exemplary. The authors are also grateful to Prof Bishnu P Pal for giving us the opportunity to contribute to this special issue of AJP dedicated to Prof Ghatak. The authors gratefully acknowledge the support from SEED grant, IIT Jodhpur.

References

1. Tomlinson W J, Stolen R H, Johnson A M, Optical wavebreaking of pulses in nonlinear optical fibers, *Opt Lett*, 10(1985)457-459.
2. Anderson D, Desaix M, Karlsson M, Lisak M, Quiroga-Teixeiro M L, Wave-breaking-free pulses in nonlinear optical fibers, *J Opt Soc Am B*, 10(1993)118 -1190.
3. Fermann M E, Kruglov V I, Thomsen B C, Dudley J M, Harvey J D, Self-similar propagation and amplification of parabolic pulses in optical fibers, *Phys Rev Lett*, 84(2000)6010-6013.
4. Kruglov V I, Peacock A C, Harvey J D, Exact self-similar solutions of the generalized nonlinear Schrödinger equation with distributed coefficients, *Phys Rev Lett*, 90(2003)113902; doi.org/10.1103/PhysRevLett.90.113902
5. Serkin V N, Hasegawa A, Belyaeva T L, Nonautonomous solitons in external potentials, *Phys Rev Lett*, 98(2007)074102; doi.org/10.1103/PhysRevLett.98.074102
6. Ponomarenko S A, Agrawal G P, Interactions of chirped and chirp-free similaritons in optical fiber amplifiers, *Opt Express*, 15(2007)2963-2973.
7. Ponomarenko S A, Agrawal G P, Do soliton like self-similar waves exist in nonlinear optical media?, *Phys Rev Lett*, 97(2006)013901; doi.org/10.1103/PhysRevLett.97.013901
8. Kruglov V I, Peacock A C, Harvey J D, Dudley J M, Self-similar propagation of parabolic pulses in normal-dispersion fiber amplifiers, *J Opt Soc Am B*, 19(2002)461-469.
9. Finot C, Millot G, Billet C, Dudley J M, Experimental generation of parabolic pulses via Raman amplification in optical fiber, *Opt Express*, 11(2003)1547-1552.
10. Ilday F Ö, Buckley J R, Clark W G, Wise F W, Self-similar evolution of parabolic pulses in a laser, *Phys Rev Lett*, 92(2004)213902; doi.org/10.1103/PhysRevLett.92.213902 .
11. Finot C, Millot G, Dudley J M, Asymptotic characteristics of parabolic similariton pulses in optical fiber amplifiers, *Opt Lett*, 29(2004)2533-2535.
12. Hirooka T, Nakazawa M, Parabolic pulse generation by use of a dispersion-decreasing fiber with normal group velocity dispersion, *Opt Lett*, 29(2004)498-500.
13. Biswas P, Adhikary P, Biswas A, Ghosh S, Formation and stability analysis of parabolic pulses through specialty microstructured optical fibers at 2.1 mm, *Opt Commun*, 377(2016)120-127.
14. Finot C, Barviau B, Millot G, Guryanov A, Sysoliatin A, Wabnitz S, Parabolic pulse generation with active or passive dispersion decreasing optical fibers, *Opt Exp*, 15(2007)15824-15835.
15. Lavdas S, Driscoll J B, Jiang H, Grote R R, Osgood R M, Panoiu N C, Generation of parabolic Similaritons in tapered silicon photonic wires: Comparison of pulse dynamics at telecom and mid-infrared wavelengths, *Opt Lett*, 38(2013)3953-3956.
16. Finot C, Provost L, Petropoulos P, Richardson D J, Parabolic pulse generation through passive nonlinear pulse reshaping in a normally dispersive two segment fiber device, *Opt Express*, 15(2007)852-864.
17. Iakushev S O, Shulika O V, Sukhoivanov I A, Passive nonlinear reshaping towards parabolic pulses in the steady-state regime in optical fibers, *Opt Commun*, 285(2012)4493-4499.
18. Finot C, Dudley J M, Kibler B, Richardson D J, Millot G, Optical parabolic pulse generation and applications, *IEEE J Quantum Electron*, 45(2009)1482-1489.
19. A C, Wright L, Wise F, Ultrafast fiber lasers based on self-similar pulse evolution: a review of current progress, *Rep Prog Phys*, 78(2015)113901; doi.org/10.1088/0034-4885/78/11/113901
20. Biswas P, Pal B P, Biswas A, Ghosh S, Toward self-similar propagation of optical pulses in a dispersion tailored, nonlinear, and segmented Bragg-fiber at 2.8 μm, *IEEE Photonics J*, 9(2017)1-12.
21. Joannopoulos J D, Johnson S G, Winn J N, Meade R D, *Photonic Crystals Molding the Flow of Light*, (Princeton University Press), 2008.

22. Dasgupta S, Pal B P, Shenoy M R, Nonlinear spectral broadening in solid-core Bragg fibers, *J Lightwave Technol*, 25(2007)2475-2481.
23. Agrawal S, Nonlinear Fiber Optics, (Academic Press), 2007.
24. Bracun D, Selak L, Optical probing for cnc machining of large parts made from fiber-reinforced polymer composite materials, *The Int J Adv Manuf Technol*, 100(2019)1855-1865.
25. Ilev I K, Waynant R W, *Mid-infrared Semiconductor Optoelectronics*, (Springer London, London), chap. Mid-infrared Biomedical Applications, 2006, pp 615-634.
26. Curtis A, Banishev A, Shaw W, Dlott D, Laser-driven flyer platesfor shock compression science: Launch and target impact probed by photon doppler velocimetry, *Rev Sci Instruments*, 85, 043908(2014); doi.org/10.1063/1.4871361.
27. Nakajima Y, Nishiyama A, Minoshima K, Mode-filtering technique based on all-fiber-based external cavity for fiber-based optical frequency comb, *Opt Express*, 26(2018)4656-4664.

[Received: 28.09.2019]

Somnath Ghosh

Dr. Somnath Ghosh, is currently an Assistant Professor in Indian Institute of Technology Jodhpur, Rajasthan, India. He is also the Associate Dean (Academics PG) at IIT Jodhpur from 2018 onward. He has been working in photonics over 10 years and his research work revolves around the domain of photonics which exclusively includes behavioural study of light through random disordered lattices, specially optical fibers and certain unconventional photonic devices that hold hidden singularities within. To date, he has a total of 106 publications including international journals, conferences, international and national workshops and several invited talks.

He is also reviewer of 27 reputed international journals namely Scientific Reports (Nature), Optics Express (USA), Optics Letters, IEEE Photonics Journal and many more. Earlier, Dr. Ghosh completed his Bachelor in Science from University of Calcutta in Physics. He obtained his Master in Science from Indian Institute of Technology Kharagpur (IITKGP) in Physics with specialization in Optics and Photonics. Later, he joined Indian Institute of Technology Delhi (IITD) to pursue his Ph D in Photonics. During his Ph. D., he has obtained a number of best research paper awards for his excellent work. Also, he had visited Heriot-Watt University and City University, London as a Visiting Researcher from 2008 to 2010. In 2013, he was awarded as INSPIRE Faculty by Indian National Science Academy and DST, India. He is also a former faculty of Institute of Radio Physics and Electronics, University of Calcutta.

Piyali Biswas

Piyali Biswas, is a Ph D student at Department of Physics in Indian Institute of Technology Jodhpur from 2017 onward. She works in the field of high energy pulse propagation through various linear, nonlinear, and time-varying structures. Her research revolves around the stable delivery of high energy pulses through specially designed photonic crystal fibers and also non-reciprocal pulse propagation through time-dynamic linear systems. She has 4 publications in international journals such as Optics Letters, IEEE Photonics Journal etc. and 11 international conferences and workshops.

Earlier, she obtained her Bachelor in Science degree in Physics from University of Calcutta. Later, she joined Institute of Radio Physics and Electronics, University of Calcutta to obtain Post-B. Sc. 3 year B. Tech degree and also pursued M. Tech from the same department with the specialization in Photonics and Nanoelectronics.