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We report the observation of the longitudinal soliton tunneling effect in axially-varying optical fibers. A fundamental soliton, initially propagating in the anomalous dispersion region of a fiber, can pass through a normal dispersion barrier without being substantially affected. We perform experimental studies by means of spectral and temporal characterizations that show the evidence of longitudinal soliton tunneling process. Our results are well supported by numerical simulations using the generalized nonlinear Schrödinger equation.

**OCIS codes:** (190.4370) Nonlinear optics, fibers; (190.5530) Pulse propagation and temporal solitons.

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A temporal optical soliton is a shape invariant localized pulse resulting from the balance between focusing Kerr nonlinearity and anomalous group velocity dispersion (GVD) [1]. Since the very first introduction of the word soliton in plasma physics, particular emphasis was given to the particle-like nature of these waves [2]. Solitons can collide elastically between each other [3] and can survive severe perturbations, like Raman effect [4], high-order dispersion [5] or the interaction with linear waves [6]. Studies of the scattering of a soliton approaching a potential have shown a dynamics similar to the quantum particle case [7] in terms of transmission or reflection by the potential barrier. In particular, a soliton has the ability to tunnel through a potential in analogy with the quantum tunneling effect [8–10]. The similarity between optical tunneling in fibers and quantum tunneling has been pointed out, for example, in [11] in the spectral domain, where the potential barrier is mimicked by a sign change of GVD [12]. The spectral tunneling effect was also experimentally studied in microstructured fibers [13, 14]. In these works, the fiber was designed to have two closely-separated zero dispersion wavelengths (ZDWs), so that two different anomalous GVD regions are separated by a narrow normal GVD region, acting as a potential barrier. A soliton propagating in the first anomalous GVD region is red-shifting via self-induced Raman scattering until it reaches one ZDW, where the frequency shift stops [4].

This cancellation of the Raman self-frequency shift is accompanied by the emission of a phase-matched dispersive wave across the ZDW. When the dispersion profile is properly designed, the phase-matched dispersive wave will be emitted across the potential barrier in the second, long wavelength side anomalous GVD region, where solitons can exist. Therefore, there is a continuous flow of energy from the initial soliton to the emitted dispersive wave, which in turn may lead to the formation of a new soliton, resulting in an overall soliton tunneling effect across the GVD barrier.

In the present work, we propose and study, both numerically and experimentally, a different kind of optical soliton tunneling which is, once again, analogous to the quantum tunneling effect. In this case, the potential barrier is a short normal GVD fiber segment, placed between two anomalous GVD fiber sections. The soliton propagation in such a system can be divided into three parts. In the initial stage, we generate a soliton propagating in a fiber with anomalous GVD. After some propagation distance, the soliton reaches the normal GVD barrier, where it cannot exist anymore as a soliton, and thus it excites a dispersive pulse. Finally, the pulse reaches the final anomalous GVD segment, where it reshapes once again into a soliton.

Let us begin our study with numerical simulations based on the generalized nonlinear Schrödinger equation (GNLSE) [15]:

\[ i\partial_z A + D(i\partial_t z)A + \gamma A \int |R(t')|^2 |A(t-t')|^2 dt' = 0 \]  

where the dispersion operator \( D(i\partial_t) = \sum_{n\geq 2} \frac{n^2}{2!} (i\partial_t)^n \) takes into account the dispersion profile of the fiber up to \( n = 3 \) and where \( \gamma \) is the nonlinear parameter. \( R(t) = (1 - f_R)\delta(t) + f_Rh_R(t) \) includes both Kerr and Raman effects, where \( h_R(t) \) correspond to the Raman response function (\( f_R = 0.18 \)). \( D(i\partial_t) \) is expanded around \( \omega_p \), the pump carrier frequency, and \( t \) is the retarded time in the frame traveling at the group velocity \( V_g = V_p(\omega_p) = \beta_2^{-1} \) of the pump pulses. We have verified that the self-steepening term does not play any important role.

We consider a concatenation of three dispersion shifted fiber (DSF) segments with different values of ZDW. The present study is made with a view to experiments, thus we choose all parameters in the range of available fibers. Accordingly, the first section has a ZDW equal to 1385 nm and a length of 50 m. Next, the ZDW of the second fiber (acting as the barrier at the origin of the tunneling effect) goes up to 1700 nm for 3 m. Finally, the ZDW of the third 50 m long fiber segment drops down to 1490 nm. In this last section, the ZDW was set higher than the ZDW of the first section, in order to excite a low order soliton after the normal GVD barrier, when taking into account the soliton Raman self-frequency shift (SSFS) of the incident soliton in the...
first fiber segment. The pump is set to our available laser i.e. a Gaussian pulse centered around 1485 nm and with a full width at half-maximum (FWHM) duration of 220 fs. At this wavelength, the nonlinear parameter $\gamma$ is about 5 $(W.km)^{-1}$ and the third order dispersion $\beta_3$ is equal to 5 $ps^3/m$ for all sections.

From about 60 m, we can identify the formation of two solitary pulses ($S_1$ and $S_2$) which reach 1547 nm and 1590 nm at 100 m, respectively. Simultaneously, two small radiative waves are generated at 1375 nm and 1416 nm, which is consistent with the known picture of the generation of dispersive waves from solitons [5]. Indeed, it can be verified that $S_1$ and $R_1$ on one hand, and $S_2$ and $R_2$ on the other hand both satisfy the phase matching relation linking dispersive waves to solitons [5]. So at this point, it appears that the initial soliton has been able to tunnel through the normal GVD barrier, giving rise to two solitons after the potential barrier.

To get further insight into this process, we studied its dynamics in the time domain. Figure 2(a) shows the temporal profile along the propagation distance in the fiber, whereas Fig. 2(b) illustrates the temporal profile at the end of the initial 50 m long anomalous GVD section (blue curve), at the end of the second normal GVD segment (green curve), and at the end of final anomalous GVD section (red curve), respectively. At the initial stage, the soliton rapidly separates from the pump $P$ and strongly decelerates due to SSFS, as observed in the spectral domain in Fig. 1. The soliton reaches the normal GVD fiber section input at 50 m (at around 8 ps in the plot), with a FWHM duration of 118 fs [blue curve in Fig. 2(b)]. Inside the second fiber section, the pulse strongly broadens temporally due to normal GVD. At the end of this segment (at 53 m), the pulse loses its hyperbolic secant shape and it acquires a Gaussian profile, with a FWHM duration of 784 fs [green curve in Fig. 2(b)], which is more than 6 times the FWHM duration at the input of the normal GVD fiber (50 m). Afterwards, the pulse enters the final anomalous dispersion fiber section, where it temporally recompresses and reshapes into a fundamental soliton. By comparing with the soliton entering the tunnel, the peak power of this soliton $S_1$ is reduced by a factor of about 2, while its duration is about the same. A second weak pulse $S_2$ can also be observed around 9.5 ps at the end of the third fiber. Performing a simulation over a much longer distance of 200 m, we noticed that the $S_2$ pulse remains stable as a second (weak) soliton. A radiation peak corresponding to $R_1$ is observed from 60 m in Fig. 2(a). The second radiation peak $R_2$ is too weak to be seen on this plot, although we verified its presence by adapting the colorscale (not shown here). These results provide a theoretical evidence of the process of longitudinal soliton tunnelling, in which a soliton can tunnel through a potential barrier made of a short normal GVD fiber section.

Fig. 1. Numerical simulation of experiments demonstrating the longitudinal soliton tunneling effect. Simulated spectrum against the fiber length. The black line corresponds to the ZDW and $R_1$, $R_2$, $P$, $S_1$, $S_2$ respectively stand for the different components of the output spectrum: radiation 1 and 2, pump residue, soliton 1 and 2.

Fig. 2. (a) Simulated temporal profile against the fiber length. The dashed horizontal lines mark the normal GVD tunnel. (b) Temporal profile respectively at $z = 50$ m (blue), $z = 53$ m (green) and at the fiber output $z = 100$ m (red).
In order to study the soliton tunneling effect experimentally, we constructed a composite fiber by splicing three dispersion shifted fibers with length and ZDW corresponding to the parameters of the previous numerical simulations. In particular, the length of the intermediate normal GVD fiber was set to 3 m. We used an optical parametric oscillator (OPO) pumped by a Ti:Sa laser to generate the initial soliton. Our source delivers Gaussian pulses of 220 fs FWHM duration, which are tuned to λ_{pump} = 1485 nm. The pulse power was controlled by means of a half wave plate and polarizers, and was set to P_{peak} = 240 W. We used an optical spectrum analyzer to perform spectral measurements at the fiber output. The result is shown in Fig. 4, where we compare the experimental spectrum at the composite fiber output (z = 100 m, red line) with the spectrum measured at the input of the normal GVD section (z = 50 m, black line) after a cutback. In Fig. 4 we can clearly identify the incident soliton entering the normal GVD section at 1528 nm (black line), along with the two output solitons around 1536 nm (S_2) and 1597 nm (S_1) on the red curve. In the output spectrum, we also see the two dispersive waves (R_1 around 1365 nm and R_2 around 1420 nm) generated from the two solitons S_1 and S_2, in excellent agreement with the previous numerical simulations.

In addition to these spectral measurements, we performed autocorrelation measurements after successive cutbacks of the fiber. This allowed us to follow the evolution of the main soliton temporal duration versus fiber length. To do that, the main soliton was spectrally filtered and sent to a second harmonic generation autocorrelator. Figures 5(a), (b) and (c) show three examples of experimental autocorrelation traces (red dashed lines) recorded at 50 m (i.e. in the initial anomalous GVD fiber), at 53 m (i.e. at the end of the normal GVD section) and at 93 m (in the final anomalous GVD fiber), respectively. In both anomalous GVD fiber segments, auto-correlations are well fitted by square hyperbolic secant functions (black lines), while in the normal GVD fiber, the optimal fitting function is Gaussian (black line). These measurements as well as additional ones are shown in Fig. 5(d) as red full circles, together with the simulation result (black solid line), which turns out to be in excellent agreement. One can see that the pulse quickly spreads in time when it enters in the normal GVD fiber “potential barrier” at 50 m. The maximum FWHM duration (690 fs) is observed when the pulse reaches the end of this fiber segment (z = 53 m). As soon as the pulse enters the final anomalous GVD fiber section, it recompresses in time until it reaches 60 m, where the duration progressively stabilizes to around 125 fs, in excellent agreement with the simulation results. Its wavelength is 1590 nm, again in full accordance with numerical predictions. These autocorrelation measurements...
confirm the solitonic nature of the pulse before and after the normal GVD fiber section, and thus provide a clear experimental confirmation of the longitudinal soliton tunnelling effect.

To conclude, we observed for the first time to our knowledge, a new kind of optical soliton tunneling where a soliton can longitudinally pass through a normal GVD fiber section without experiencing substantial modifications of its properties. In analogy with the quantum tunneling effect, in which the transmission is set by the potential barrier strength, the length of the normal GVD fiber acting as the potential well has a strong influence on the efficiency of the process. Longitudinal soliton tunneling provides a fundamentally new example of optical invisibility (of the potential well barrier) which may find applications to the cloaking of information.

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