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Spatiotemporal-dressed optical solitons in hollow-core capillaries

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Abstract: The nonlinear propagation of a laser beam in a hollow-core capillary is studied by solving the spatiotemporal nonlinear propagation equation. Although we assume to initially couple the light into only one high spatial mode of the capillary, we have identified that the beam can propagate as a new type of multi-mode solitonic structure, the spatiotemporal-dressed soliton, which consists of a mixture of spatial modes in which one has most of the energy while the rest of them, with small contributions, module (dress) the propagation of the main spatial mode. As a consequence of such behavior, we observe a clean self-compression process, obtaining a pulse in the single-cycle limit, accompanied by a giant blue dispersive wave and a new type of multi-mode dispersive wave that appears in the mid-IR region.

1. Introduction

Soliton formation is one of the most fascinating nonlinear effects. It was first reported in 1844 when John Scott Russell saw a water wave traveling in a channel without changing its shape [1]. Since then solitons have been observed in other fields besides fluids, such as in Bose-Einstein condensates [2] or light [3,4]. Optical solitons, that are localized waves in the temporal coordinate, were first observed in optical fibers [5] with an enormous interest due to their possible application for optical communications [6]. Thenceforth the optical community has used optical fibers, or similar systems, to study many nonlinear effects such as self-phase modulation (SPM) [7], stimulated Raman scattering [8], stimulated Brillouin scattering [9], etcetera.

Among all these nonlinear effects, SPM has become essential in the ultra-short pulse generation context. In 1980, Mollenauer and coworkers reported for the first time the pulse self-compression in optical fibers due to the solitonic propagation [5]. Four years later, Tomlinson and coworkers demonstrated that the compression of the pulse could also be obtained in the normal dispersion regime, with the help of an external compressor to compensate the phase acquired during nonlinear propagation in the optical fiber [10]. Later, important improvements have been introduced in the post-compression setups, especially in two directions: first, creating new compressor elements such as the chirped mirrors [11], that have helped to develop powerful compressor and diagnostic devices such as the d-scan, [12], allowing the compression of pulses down to almost the cycle limit [13]. Second, using longitudinal or transversal structured fibers to gain fine control of the propagation properties. An example of longitudinal structured fibers are the dispersion-managed fibers proposed by Hasegawa and coworkers [14]. They presented periodic evolution of the dispersion and were used to enhance the transmission of temporal solitons in the fiber. Hasegawa and coworkers demonstrated that these structured fibers have a center solitonic solution that guides the evolution of the whole pulse, that they called *dressed-soliton*. Transverse structured fibers, such as hollow-core photonic crystal fibers (HC-PCFs), have enormous capabilities in the context of nonlinear optics because they can be designed to guide the light through the hollow core, presenting the suitable dispersion response needed for a broad number of applications, [15, 16], with special relevance in the ultra-short pulse generation context [17–19].

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Nowadays there is an increasing interest in studying nonlinear effects in multi-mode (MM) fibers. The MM systems have the difficulty of showing a complex spatio-temporal evolution, but they present other nonlinear ingredients that could be interesting for a variety of effects, such as the super-continuum generation in MM HC-PCFs [20], the optical soliton formation or other spatio-temporal effects observed in graded-index MM optical fibers [21–24], the presence of vector soliton solutions on step-index MM optical fibers [25], or the self-compressed pulse generated using high-spatial modes in hollow-core capillaries (also called hollow-core fibers HCFs) [26], to mention just some examples. Moreover, the extraordinary control that can be achieved nowadays allows us to couple the light in a single high order mode of a hollow-core fibre [27, 28], and also of a hollow-core photonic crystal fiber [29, 30]. In this article, we will be dealing with a multi-mode HCF in which the interaction between the different spatial modes, even those with a small contribution, is essential to understand the nonlinear propagation dynamics. In particular, we will show a new solitonic structure based on a high spatial mode sustained by small contributions of other spatial modes. We will call it a spatiotemporal-dressed optical soliton.

2. Self-compression dynamics in hollow-core fibers

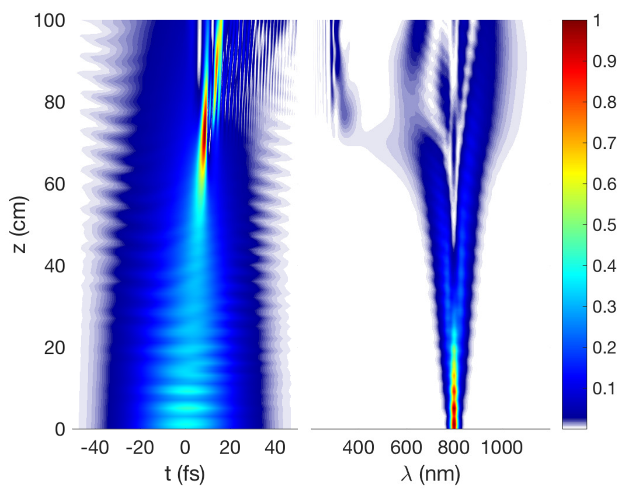

Fig. 1. Evolution of the normalized on-axis temporal (left) and spectral (right) intensity distribution of a 35 fs FWHM laser pulse, with 75 μJ of energy and coupled to the second high spatial mode (HE_{13}) of a 1 meter long HCF with 150 μm core radius filled with 1 bar of argon.

We have recently demonstrated that, although the higher spatial modes of the HCF (the HE_{1m} modes with $m > 1$) have non-negligible losses, they present anomalous dispersion response in the near infrared spectral region that could lead to the activation of self-compression processes [26]. Figure 1 shows the theoretical self-compression dynamics of the second excited spatial mode (HE_{13}) propagating in a 1 meter long HCF with 150 μm core radius (r_F) filled with 1 bar of argon. The pulse is a 35 fs laser pulse (at full width at half maximum (FWHM)) with 75 μJ of energy. The input beam used in the simulation has the following form:

$$E(r,t) = E_0 J_0 (u_3 r / r_F) \exp\left(-t^2/t_p^2\right), \tag{1}$$

where $u_3 \approx 8.65$, the third zero of the J_0 Bessel function, so initially the beam only contains the HE_{13} mode, and $t_p = 30$ fs. All the linear dispersion terms are taken into account by using the

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formula of the refractive index of argon obtained in [31]. As shown in Fig. 1, a self-compressed single-cycle pulse with a FWHM of 2.2 fs is obtained at around 75 cm. These results are obtained from the standard nonlinear envelope spatio-temporal equation adapted to simulate the nonlinear propagation of a laser pulse in a HCF [32], in which the linear propagation is done by decomposing and propagating the field through the HCF modes, while the nonlinear terms are solved with a standard fourth-order Runge-Kutta algorithm. A similar model has been successfully applied to the nonlinear propagation in planar hollow waveguides [33, 34]. As usual, our model assumes cylindrical symmetry and takes into account the whole modal-dispersion and absorption linear response of the first 30 linearly polarized leaky modes of the HCF [35], together with the most relevant nonlinear effects: SPM, self-steepening and ionization (modeled with the well-known Perelemov-Popov-Terentev (PPT) model [36]). All the results presented here do not include any noise in the input beam, but we have checked that adding white noise to the phase of the input beam does not alter the dynamics. For more details on the simulation see [26, 32].

The dynamics shown in Fig. 1 are common in nonlinear pulse propagation in anomalous dispersion regime [37]. They are often explained with the help of the soliton order parameter, $N = \sqrt{L_D/L_{NL}}$ [38], where $L_D = t_0^2/|\beta''|$ and $L_{NL} = c/n_2 I_0 \omega_0$ represent the dispersion and nonlinear lengths, respectively. These characteristic lengths are defined for a pulse of duration t_0, with peak intensity I_0 and centered at frequency ω_0, propagating in a medium with a group velocity dispersion (GVD) β'' and nonlinear refractive index n_2, where c represents the speed of light in vacuum. Note that these lengths, and the soliton order parameter, are defined neglecting the losses and any possible spatial dynamics. Large values of the soliton order parameter indicate complex nonlinear dynamics due to the progressive appearance of the modulation instability [37, 39].

For the parameters used in Fig. 1 ($t_0 = 35$ fs, $\beta'' = -0.055$ fs^2/mm, $n_2 = 1.74 \times 10^{-19}$ cm^2/W and $\lambda_0 = 800$ nm) the soliton order takes the value $N = 34$ which should correspond to a quite strong nonlinear interaction but has nothing to do with the self-compression process observed, which typically appears for $N \sim 3 - 8$ [37]. The discrepancy between the dynamics predicted by the soliton order parameter and what we obtain with the spatio-temporal simulations is not surprising, because it is possible that a pure temporal model, such as the one behind the soliton order parameter, could not describe properly our MM guiding system [20]. To see if we really need a complete spatio-temporal simulation, we show in Fig. 2 (top) the percentage contribution of the lowest six spatial modes along the HCF for the same parameters used in Fig. 1. The contribution of the main mode (HE_{13}) is shown in the inset (being always >92%), while the other five modes are presented in the main plot (being all <5%). Although Fig. 2 (top) seems to indicate that we are dealing with a single-mode propagation scenario and, in fact, there is no appreciable change in the spatial characteristics of the beam along the whole propagation, we will demonstrate that the presence of the small contributions of other spatial modes is essential to understand the observed propagation. Figure 2 (bottom) shows the temporal intensity distribution on-axis for the lowest six spatial modes at three different propagation distances, where we show the small contribution of some spatial modes that will help us to understand the new nonlinear scenario. The situation shown here is completely different to that presented by Wright and coworkers, [40], where they discussed a case in which several spatial modes, all of them presenting similar contributions, evolve as a multi-mode optical soliton. In our case, we have a single-mode soliton affected (dressed) by the small contributions of other spatial modes. We have called this new type of solitonic dynamics a spatiotemporal-dressed optical soliton.

3. Spatiotemporal-dressed optical solitons: a simple model demonstration

To demonstrate that the small contributions of spatial modes (the spatial dressing) have an important influence on the propagation of the main mode, we have developed a simple temporal nonlinear propagation model, a 1D model, including the same linear and nonlinear effects as the

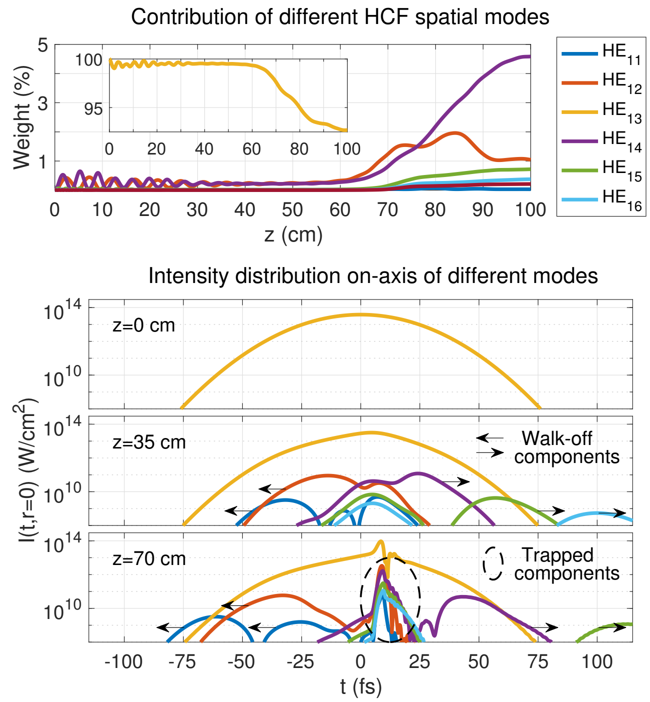

Fig. 2. Percentage weight of the first 6 spatial modes along the propagation (top). Their temporal intensity distribution on-axis in log. scale at three distances inside the HCF (bottom). Both plots are done for the same parameters of Fig. 1 and share the color code of the legend (see Visualization 1 for the complete evolution in the first 80 cm of the HCF).

complete spatio-temporal simulation, but neglecting the spatial dynamics. The results obtained are presented in Fig. 3 (top) where we show the temporal and spectral intensity evolution for the same input parameters used in Fig. 1. It is evident that the simple 1D-model does not reproduce the results obtained with the complete 2D-model, demonstrating the pure spatio-temporal nature of the propagation in this situation. To better compare both simulations, Fig. 3 shows the comparison between the evolution of the FWHM pulse temporal duration (middle) and the FWHM spectrum width (bottom) for the two models (2D-model in blue and 1D-model in orange). As we can see, the temporal compression and the spectral broadening are much more intense in the 1D-model, as the soliton order parameter predicted. In fact, we could compute some other distances related to the nonlinear dynamics observed, such as the self-compression distance $L_{SC} \approx \sqrt{L_{NL} L_D/2}$ [41], for which we obtain a value of 35 cm, which agrees quite well with the 1D-model but not with the 2D-model.

It is clear that the spatial dynamics cannot be neglected when studying the nonlinear propagation in standard HCFs. Although the amount of energy transferred to other spatial modes is low, this nonlinear transfer process occurs along all the HCF and ends up affecting the propagation of the main spatial mode. The bottom plots of Fig. 2 show clearly this transfer process and the role played by the new spatial modes, which has two components. One propagates almost linearly, with a group velocity very close to the one determined by the HCF modal dispersion [35]. This component suffers a clear temporal walk-off, as can be seen in Fig. 2 (bottom) for z=35 and 70 cm, and interferes with the main mode, generating a beating in the spatio-temporal intensity distribution that can be observed in the oscillations of the evolution of the pulse duration, the

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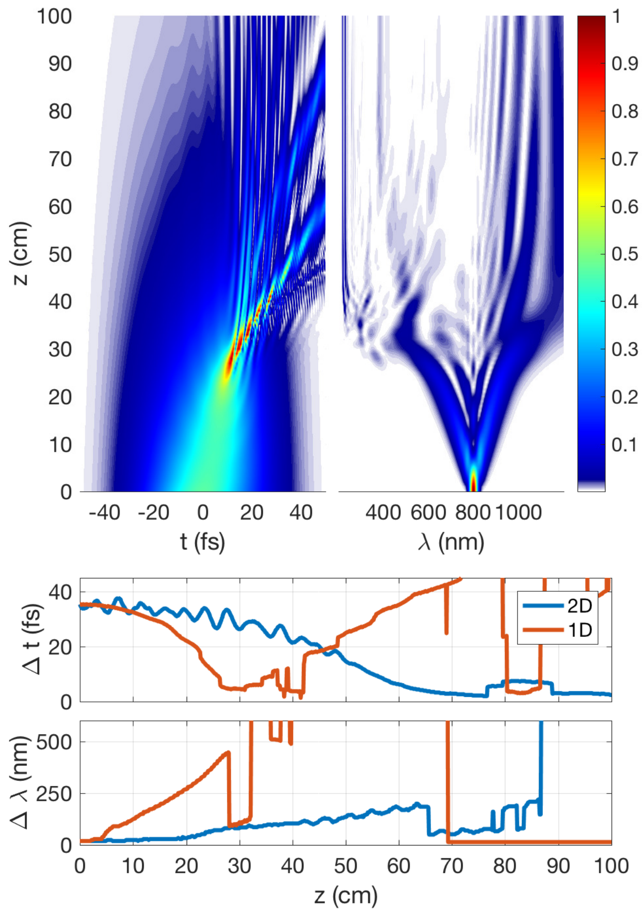

Fig. 3. Evolution of the normalized temporal (top left) and spectral (top right) intensity distribution obtained from the 1D-model for the same parameters as in Fig. 1. Comparison of the evolution of the FWHM temporal (middle) and spectral widths (bottom) for the two models.

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blue line of Fig. 3 (middle)) [42]. Obviously, this component ends up isolated from the main mode and cannot be responsible for the dressing process. On the contrary, the second component of the secondary spatial modes is trapped by the main mode, generating the oscillations shown in the top plot of Fig. 2. This latter component is connected to the main mode during the whole self-compression process. We say that this component of the secondary modes dresses the main one. The nonlinear energy transfer between the dressing modes and the main one reduces the nonlinear efficiency of the latter, softening its nonlinear propagation and generating a new type of multi-mode solitonic dynamics: the spatiotemporal-dressed solitons.

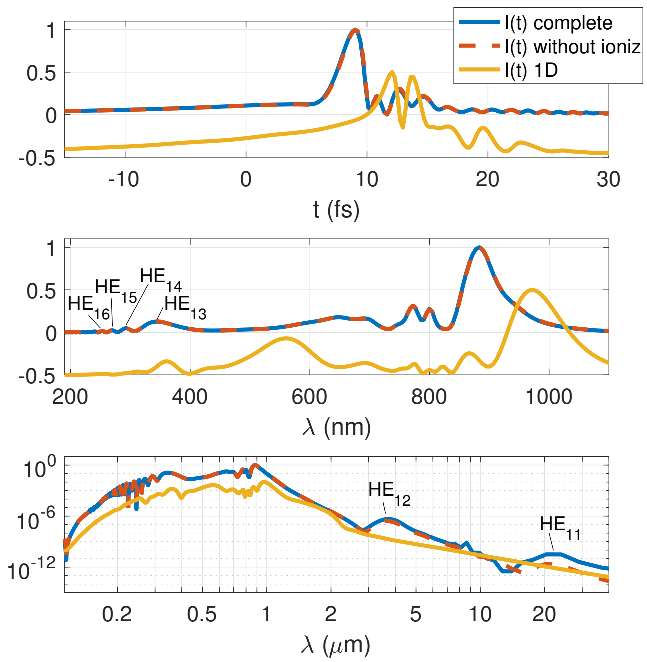

Fig. 4. Best self-compressed pulse obtained with the two numerical models. The figure shows the temporal intensity distribution (top) and spectrum (middle in linear scale and bottom in log. scale). The continuous blue and yellow lines are the structures obtained with the 2D-model (at 75 cm) and the 1D-model (at 30 cm), respectively. The dashed orange lines are the results obtained when turning off the ionization in the 2D-model (at 75 cm). The results corresponding to the 1D-model are vertically shifted for clarity.

Finally, we should remark that the formation of this new spatiotemporal-dressed soliton has interesting properties, besides the obvious single-cycle self-compression result. The first relevant effect, shown in the middle plot of Fig. 4 and in the final part of the spectrum in Fig. 1, is the generation of the standard dispersive wave (DW), typically observed during the propagation of a pulse with low N in anomalous dispersion media [37]. It is well known that the DW appears when there is an energy transfer from a self-compressed soliton (propagating in the anomalous response region) to a new pulse (propagating in the normal response region, usually at the blueish spectral part) under perfect phase-matching conditions [43]. In our case, this transfer process can be done from the soliton towards the normal dispersion frequencies of the main mode, but also towards the normal dispersion frequencies of other higher order modes. As a consequence we obtain an extraordinary large DW comb, each spike coming from a different spatial mode. Moreover, the presence of spatial modes of lower order than the main one (HE_{11} and HE_{12}) opens a new DW generation scenario because they have a different phase matching condition that is fulfilled in the mid-infrared (mid-IR) spectral region, as shown in the bottom plot of Fig. 4. Similar mid-IR DWs have been identified before, although in different contexts: in a study devoted to the generalization of the dispersive wave emission process [44], or as the Stoke four-wave mixing emission in a hollow-core photonic crystal fiber [45], or as an effect induced by the plasma generated in HC-PCF [46], recently proved experimentally [47]. In our case the origin of the mid-IR DW is completely different, coming directly from the modal dispersion of the HCF modes (see that those mid-IR peaks do not appear for the 1D model, which does not include spatial modes). In order to verify that the ionization is not the origin of this mid-IR DW we have done simulations of the 2D-model without ionization (shown in Fig. 4 with an orange dashed line). It can be seen that ionization plays a minor role both in the DW generation process and in the general dynamics, although note that the DW associated to the fundamental mode has some enhancement due to the presence of the plasma.

4. Conclusions

In summary, we have found a new type of multi-mode solitonic structure: the spatiotemporal-dressed soliton. This type of solution appears when the beam is composed of several spatial modes, one of them having a much greater contribution than the rest. In spite of their small contribution, the rest of spatial modes affect the propagation of the main one, dressing it. We have found this new type of solitonic structure during the propagation of a higher order spatial mode in a HCF. As a result of the nonlinear propagation of this multi-mode structure, we observe a clean self-compression, close to the single-cycle regime, thanks to the giant blue dispersive wave induced during the temporal compression process. Another unique property, linked to the multi-mode nature of this propagation, is the appearance of a new type of dispersive wave in the mid-IR spectral region, paving the way to the generation of ultra-broadband spectra.

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References

1. J. S. Russell, "Report on waves," in *Report of the 14th Meeting of the British Association for Advancement of Science, York* (1844), pp. 311–390.
2. L. Khaykovich, F. Schreck, G. Ferrari, T. Bourdel, J. Cubizolles, L. D. Carr, Y. Castin, and C. Salomon, "Formation of a matter-wave bright soliton," Science **296**, 1290–1293 (2002).
3. K. D. Moll, A. L. Gaeta, and G. Fibich, "Self-similar optical wave collapse: observation of the townes profile," Phys. Rev. Lett. **90**, 203902 (2003).
4. C. Ruiz, J. San Roman, C. Méndez, V. Díaz, L. Plaja, I. Arias, and L. Roso, "Observation of spontaneous self-channeling of light in air below the collapse threshold," Phys. Rev. Lett. **95**, 053905 (2005).
5. L. F. Mollenauer, R. H. Stolen, and J. P. Gordon, "Experimental observation of picosecond pulse narrowing and solitons in optical fibers," Phys. Rev. Lett. **45**, 1095–1098 (1980).
6. A. Hasegawa and F. Tappert, "Transmission of stationary nonlinear optical pulses in dispersive dielectric fibers, I. anomalous dispersion," Appl. Phys. Lett. **23**, 142–144 (1973).
7. E. P. Ippen, C. V. Shank, and T. K. Gustafson, "Self-phase modulation of picosecond pulses in optical fibers," Appl. Phys. Lett. **24**, 190–192 (1974).
8. R. H. Stolen, E. P. Ippen, and A. R. Tynes, "Raman oscillation in glass optical waveguide," Appl. Phys. Lett. **20**, 62–64 (1972).
9. E. Ippen and R. Stolen, "Stimulated Brillouin scattering in optical fibers," Appl. Phys. Lett. **21**, 539–541 (1972).
10. W. J. Tomlinson, R. H. Stolen, and C. V. Shank, "Compression of optical pulses chirped by self-phase modulation in fibers," J. Opt. Soc. Am. B **1**, 139–149 (1984).
11. R. Szipöcs, K. Ferencz, C. Spielmann, and F. Krausz, "Chirped multilayer coatings for broadband dispersion control in femtosecond lasers," Opt. Lett. **19**, 201–203 (1994).
12. M. Miranda, T. Fordell, C. Arnold, A. L'Huillier, and H. Crespo, "Simultaneous compression and characterization of ultrashort laser pulses using chirped mirrors and glass wedges," Opt. Express **20**, 688–697 (2012).

13. F. Silva, B. Alonso, W. Holgado, R. Romero, J. S. Roman, E. C. Jarque, H. Koop, V. Pervak, H. Crespo, and I. Sola, "Strategies for achieving intense single-cycle pulses with in-line post-compression setups," Opt. Lett. **43**, 337–340 (2018).
14. A. Hasegawa, Y. Kodama, and A. Maruta, "Recent progress in dispersion-managed soliton transmission technologies," Opt. Fiber Technol. **3**, 197–213 (1997).
15. R. F. Cregan, B. J. Mangan, J. C. Knight, T. A. Birks, P. St. J. Russell, P. J. Roberts, and D. C. Allan, "Single-mode photonic band gap guidance of light in air," Science **285**, 1537–1539 (1999).
16. P. St. J. Russell, P. Hölzer, W. Chang, A. Abdolvand, and J. C. Travers, "Hollow-core photonic crystal fibres for gas-based nonlinear optics," Nat. Photonics **8**, 278–286 (2014).
17. D. G. Ouzounov, F. R. Ahmad, D. Müller, N. Venkataraman, M. T. Gallagher, M. G. Thomas, J. Silcox, K. W. Koch, and A. L. Gaeta, "Generation of megawatt optical solitons in hollow-core photonic band-gap fibers," Science **301**, 1702–1704 (2003).
18. M. Nisoli, S. De Silvestri, and O. Svelto, "Generation of high energy 10 fs pulses by a new pulse compression technique," Appl. Phys. Lett. **68**, 2793–2795 (1996).
19. M. Nisoli, S. D. Silvestri, O. Svelto, R. Szipöcs, K. Ferencz, C. Spielmann, S. Sartania, and F. Krausz, "Compression of high-energy laser pulses below 5 fs," Opt. Lett. **22**, 522–524 (1997).
20. F. Poletti and P. Horak, "Dynamics of femtosecond supercontinuum generation in multimode fibers," Opt. Express **17**, 6134–6147 (2009).
21. W. H. Renninger and F. W. Wise, "Optical solitons in graded-index multimode fibres," Nat. Commun. **4**, 1719 (2013).
22. L. G. Wright, D. N. Christodoulides, and F. W. Wise, "Controllable spatiotemporal nonlinear effects in multimode fibres," Nat. Photonics **9**, 306 (2015).
23. K. Krupa, A. Tonello, B. M. Shalaby, M. Fabert, A. Barthélémy, G. Millot, S. Wabnitz, and V. Couderc, "Spatial beam self-cleaning in multimode fibres," Nat. Photonics **11**, 237 (2017).
24. O. V. Shtyrina, M. P. Fedoruk, Y. S. Kivshar, and S. K. Turitsyn, "Coexistence of collapse and stable spatiotemporal solitons in multimode fibers," Phys. Rev. A **97**, 013841 (2018).
25. A. Mecozzi, C. Antonelli, and M. Shtaif, "Coupled manakov equations in multimode fibers with strongly coupled groups of modes," Opt. Express **20**, 23436–23441 (2012).
26. B. A. López-Zubieta, E. Conejero Jarque, I. J. Sola, and J. San Roman, "Theoretical analysis of single-cycle self-compression of near infrared pulses using high-spatial modes in capillary fibers," Opt. Express **26**, 6345–6350 (2018).
27. D. Walter, T. Pfeifer, C. Winterfeldt, R. Kemmer, R. Spitzenpfeil, G. Gerber, and C. Spielmann, "Adaptive spatial control of fiber modes and their excitation for high-harmonic generation," Opt. Express **14**, 3433–3442 (2006).
28. Y. Yirmiyahu, A. Niv, G. Biener, V. Kleiner, and E. Hasman, "Excitation of a single hollow waveguide mode using inhomogeneous anisotropic subwavelength structures," Opt. Express **15**, 13404–13414 (2007).
29. T. G. Euser, G. Whyte, M. Scharrer, J. S. Y. Chen, A. Abdolvand, J. Nold, C. F. Kaminski, and P. St. J. Russell, "Dynamic control of higher-order modes in hollow-core photonic crystal fibers," Opt. Express **16**, 17972–17981 (2008).
30. A. A. Ishaaya, C. J. Hensley, B. Shim, S. Schrauth, K. W. Koch, and A. L. Gaeta, "Highly-efficient coupling of linearly- and radially-polarized femtosecond pulses in hollow-core photonic band-gap fibers," Opt. Express **17**, 18630–18637 (2009).
31. J. Zhang, Z. H. Lu, and L. J. Wang, "Precision refractive index measurements of air, N_2, O_2, Ar, and CO_2 with a frequency comb," Appl. Opt. **47**, 3143–3151 (2008).
32. E. Conejero Jarque, J. San Roman, F. Silva, R. Romero, W. Holgado, M. A. Gonzalez-Galicia, B. Alonso, I. J. Sola, and H. Crespo, "Universal route to optimal few- to single-cycle pulse generation in hollow-core fiber compressors," Sci. Reports **8**, 2256 (2018).
33. C. Arnold, S. Akturk, M. Franco, A. Couairon, and A. Mysyrowicz, "Compression of ultrashort laser pulses in planar hollow waveguides: a stability analysis," Opt. Express **17**, 11122–11129 (2009).
34. C. L. Arnold, B. Zhou, S. Akturk, S. Chen, A. Couairon, and A. Mysyrowicz, "Pulse compression with planar hollow waveguides: a pathway towards relativistic intensity with table-top lasers," New J. Phys. **12**, 073015 (2010).
35. E. A. J. Marcatili and R. A. Schmeltzer, "Hollow metallic and dielectric waveguides for long distance optical transmission and lasers," Bell Syst. Tech. J. **43**, 1783–1809 (1964).
36. A. M. Perelemov, V. S. Popov, and M. V. Terentev, "Ionization of atoms in an alternating electric field," J. Exp. Theor. Phys. **23**, 924–934 (1966).
37. J. C. Travers, W. Chang, J. Nold, N. Y. Joly, and P. St. J. Russell, "Ultrafast nonlinear optics in gas-filled hollow-core photonic crystal fibers," J. Opt. Soc. Am. B **28**, A11–A26 (2011).
38. G. P. Agrawal, "Nonlinear fiber optics," in *Nonlinear Fiber Optics* (Academic, 2001).
39. J. M. Dudley, G. Genty, and S. Coen, "Supercontinuum generation in photonic crystal fiber," Rev. Mod. Phys. **78**, 1135–1184 (2006).
40. L. G. Wright, W. H. Renninger, D. N. Christodoulides, and F. W. Wise, "Spatiotemporal dynamics of multimode optical solitons," Opt. Express **23**, 3492–3506 (2015).
41. C.-M. Chen and P. L. Kelley, "Nonlinear pulse compression in optical fibers: scaling laws and numerical analysis," J. Opt. Soc. Am. B **19**, 1961–1967 (2002).
42. M. Nurhuda, A. Suda, K. Midorikawa, M. Hatayama, and K. Nagasaka, "Propagation dynamics of femtosecond laser

pulses in a hollow fiber filled with argon: constant gas pressure versus differential gas pressure," J. Opt. Soc. Am. B **20**, 2002–2011 (2003).

43. N. Akhmediev and M. Karlsson, "Cherenkov radiation emitted by solitons in optical fibers," Phys. Rev. A **51**, 2602–2607 (1995).
44. K. E. Webb, Y. Q. Xu, M. Erkintalo, and S. G. Murdoch, "Generalized dispersive wave emission in nonlinear fiber optics," Opt. Lett. **38**, 151–153 (2013).
45. F. Tani, J. C. Travers, and P. St. J. Russell, "Multimode ultrafast nonlinear optics in optical waveguides: numerical modeling and experiments in kagome photonic-crystal fiber," J. Opt. Soc. Am. B **31**, 311–320 (2014).
46. D. Novoa, M. Cassataro, J. C. Travers, and P. St. J. Russell, "Photoionization-induced emission of tunable few-cycle midinfrared dispersive waves in gas-filled hollow-core photonic crystal fibers," Phys. Rev. Lett. **115**, 033901 (2015).
47. F. Köttig, D. Novoa, F. Tani, M. C. Günendi, M. Cassataro, J. C. Travers, and P. S. Russell, "Mid-infrared dispersive wave generation in gas-filled photonic crystal fibre by transient ionization-driven changes in dispersion," Nat. Commun. **8**, 813 (2017).