Ten years of nonlinear optics in photonic crystal fibre - progress and perspectives

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2009 marks the tenth anniversary of the first report of white-light supercontinuum generation in photonic crystal fiber. This result has created tremendous impact in the field of nonlinear fibre optics, and continues to open up new horizons in photonic science. In this article, we provide a concise and critical summary of the current state of nonlinear optics in photonic crystal fibre, identifying some of the most important and interesting recent developments in the field. We also discuss several emerging research directions and point out new links that are becoming apparent with other areas of physics.

The study of nonlinear propagation in optical fibres dates back to the early 1970’s, and the first fabrication of low loss silica fibre waveguides. Nonlinearity in fibres arises primarily from the intensity-dependent refractive index, but it is the way in which this nonlinearity and the fibre dispersion combine to influence light propagation that generates such a rich variety of dynamical effects. By the late 1980’s, for example, it was known that nonlinearity and dispersion could balance to support stable soliton propagation, yet they could also interact in the neighbourhood of the fiber zero dispersion wavelength to yield dramatic instabilities and the generation of broadband supercontinuum spectra.

The study of photonic crystal fibres (PCF) began in the early 1990’s, and was initially motivated by the desire to create fibres that guided via a photonic bandgap effect. The first successful PCFs, however, guided via an effective refractive index difference between a solid silica core and a surrounding cladding region containing a transverse microstructure of air holes. A comprehensive review of this development is to be found in Ref. 1. Although index guiding in PCF is conceptually similar to guidance in conventional fibers, it was soon realised that the
additional degrees of freedom offered by engineering the air hole geometry yielded guidance properties unattainable in standard fiber. Specifically, the strong waveguide contribution to the dispersion meant that it was possible to obtain zero dispersion wavelengths in the visible or near infrared, very far from the intrinsic material value of fused silica around 1.3 \( \mu \text{m} \).

The significance of such dispersion engineering for nonlinear optics was revealed in striking fashion at the 1999 Conference on Lasers and Electro-Optics, where Ranka et al. reported supercontinuum generation spanning 400-1500 nm using only nanojoule-energy 100 fs pulses from a modelocked Ti:Sapphire laser \([2,3]\). The key feature of the PCF used in these experiments was the fact its zero dispersion was shifted to be close to pump wavelength around 800 nm. In addition, a further contributing factor was the enhanced fibre nonlinearity due to tight modal confinement in the core. Indeed, shortly afterwards, Broderick et al. discussed nonlinearity engineering in PCF in more detail, and reported careful experimental measurements of the enhanced nonlinear phase shifts that could be obtained \([4]\).

The scene was set for a decade of work which has fundamentally altered the research landscape in nonlinear fibre optics. This research has led to numerous technological advances in high brightness source development, and established important links with other areas of physics through the application of frequency combs to precision measurements of fundamental physical constants. Many aspects of this progress have been well-documented in reviews of specific technical areas \([5-8]\), and some applications have now moved beyond the research stage into commercial products. As we shall see, technological progress continues to be made on many fronts, and research into the fundamental aspects of nonlinear propagation in PCF remains as dynamic as ever. Connections with other areas of physics continue to be made, and recent work has linked propagation effects in PCF to analogous phenomena in hydrodynamics,
thermodynamics and astrophysics. Not intended to be a comprehensive review in depth, this progress article aims to discuss a selection of these recent results, with the primary intention of illustrating how the rich diversity of PCF-based research is continuing to drive nonlinear photonics and physics in new – and sometimes unexpected - directions.

The supercontinuum revolution

The 1999 supercontinuum results attracted immediate attention because of their potential application in optical frequency metrology, allowing complex room-sized frequency chains to be replaced by compact benchtop systems. A historically-oriented account of this research and its revolutionary impact has been provided by Hall and Hänsch [9]. Interestingly, although the frequency metrology community quickly worked out how to generate stable supercontinua experimentally, developing a clear theoretical interpretation of the supercontinuum broadening took a little longer. In hindsight this is somewhat surprising as many previous studies of nonlinear fibre propagation had observed essentially the same spectral broadening processes, albeit using different source systems and generally in different wavelength regimes [10,11]. Nonetheless by around 2002, the supercontinuum generation process was well understood with the contributions of soliton fission, the Raman self frequency shift, and dispersive wave generation all identified (see [5] and references therein).

PCF-based frequency combs have now been widely adopted, and have led to many well-known successes such as precision measurements of fundamental constants of physics. With an eye on continued applications, current research is looking into ways of developing all fiber-format comb systems with broad spectral coverage, technical robustness, and high power. To
this end, advances in large mode area Yb fibre-based sources have been recently applied to
develop a frequency comb system with more than 10 W average power. Significantly, this high
power performance has been obtained at the same time as submillihertz linewidth relative to a
conventional Ti:Sapphire comb [12].

Of course frequency metrology is not the only important application of broadband
supercontinuum spectra, and there have been continued advances in fields such as spectroscopy,
microscopy and optical coherence tomography. However, some of the most interesting progress
in nonlinear applications of PCF has not involved broadband spectral generation at all, but rather
the generation of narrowband frequency components via parametric frequency conversion. An
area where this has been applied with particular success is in the generation of correlated photon
pairs for quantum information applications. In contrast to experiments using nonlinear crystals,
correlated photon pair generation in PCF at power levels suitable for multiphoton interference
experiments has been demonstrated with only milliwatts of pump power. This represents an
improvement of several orders of magnitude over bulk approaches [13]. In other recent studies,
narrowband parametric phasematching in PCF has been used to realize widely-tunable low-
threshold $\chi^{(3)}$ picosecond optical parametric oscillators [14,15]. Figure 1 shows results obtained
using such a PCF-based OPO pumped by a picosecond Ti:Sapphire laser [15]. By butt-coupling
dichroic mirrors to either end of a highly nonlinear index-guiding PCF, tunable narrowband
oscillation in the 500-700 nm range has been demonstrated at peak power thresholds of only
15 W. The possibility to simultaneously obtain broad tuning, narrowband oscillation and low
gain threshold arises because of the characteristic dispersion and nonlinearity parameters of PCF,
and may well lead to a new generation of compact visible light source when combined with laser
diode-based pump sources.
Extending the physics of supercontinuum generation

The basic features of what could be termed “orthodox” supercontinuum generation using femtosecond pulses are now well understood, and the detailed temporal and spectral structure seen in experiments is well-reproduced using realistic numerical models. Interestingly, although the essential nonlinear propagation equations of fibre optics have been clearly expressed in the literature for many years, the recent studies of supercontinuum generation have dramatically highlighted the quantitative predictive power of careful numerical modelling. Simulations have played a central role in revealing a number of subtle features of the nonlinear spectral broadening processes, such as coupling between the Raman and modulation-instability gain processes, and the effect of dispersion in the nonlinear response due to variation in the effective mode area in the fibre [5].

In addition, the continued application of new diagnostic techniques, and studies of supercontinuum generation using a wider range of pump sources has led to improved physical insight and sometimes unexpected analogies with other areas of physics. For example, the use of time-frequency spectrograms allows improved visualization of the femtosecond soliton propagation dynamics, and clarification of how spectral components on the long and short wavelength edges of the supercontinuum spectrum can interact despite frequency separations approaching an octave. Specifically, cross-phase modulation from long-wavelength solitons undergoing the soliton self-frequency shift has been shown to lead to energy localization or trapping in the normal dispersion regime, and the extension of the short wavelength edge of the supercontinuum. Although this effect had been noticed in earlier studies in more conventional fibres [10, 16], the results in PCF have motivated new theoretical work using a gravitational force analogy to provide analytic insight into the observed spectral structure [17]. More recent
research has also used a gravity-like analogy to speculate that features of supercontinuum generation dynamics can be interpreted in terms of an event-horizon, an effect usually associated with astrophysical black holes [18]. Another form of trapping in supercontinuum generation has also been recently seen for the first time in PCF. Specifically, a series of careful experiments have used cut-back measurements to reveal the presence of novel long-wavelength bound states where two ejected solitons from the initial soliton fission mechanism become trapped by their mutual nonlinear interaction [19].

Other current research into supercontinuum generation is studying the spectral properties observed using picosecond and nanosecond pulses from compact and relatively inexpensive pump sources. With such long pulses, however, the generated spectra typically suffer from shot-to-variations induced by modulation instability, and this can be a limiting factor in some potential applications. There is thus significant interest in developing techniques that allow a degree of control into the shaping and stability of supercontinuum generation in this regime.

Improved understanding into the mechanisms underlying these fluctuations has recently been provided through measurements of shot-to-shot statistics in a picosecond pumped supercontinuum [20]. Of particular interest is the fact that fluctuations in the supercontinuum spectral structure were shown to be associated with the generation of “optical rogue waves” – statistically rare events associated with the extreme red shift of long wavelength Raman soliton pulses. Because these fluctuations have their origin in modulation instability, there are intriguing connections with the infamous and destructive freak waves observed on the surface of the ocean. Subsequent studies have examined these instabilities in more detail, focusing on the interaction dynamics of the initial instability growth and Raman soliton propagation [21]. In fact, inspired by previous studies of induced modulation instability in the context of ultrashort pulse train...
generation, recent work has shown that induced supercontinuum generation using dual frequency fields can significantly modify the supercontinuum spectral characteristics [22, 23].

Whilst the first experiments on supercontinuum generation used femtosecond duration sources, work was rapidly extended to picosecond duration pumps. More recently, the availability of high power and compact nanosecond and quasi-CW sources has motivated much interest in experimental and theoretical studies of supercontinuum generation in this regime. With the choice of an appropriate fibre dispersion profile, experiments have reported supercontinua with 10’s of watts average power and output spectral densities of up to 100 mW/nm [24, 25]. Significantly, numerical modelling has also shown that, even in this regime, trapping and scattering of dispersive waves by high energy solitons plays a dominant role in extending the spectral bandwidth to shorter wavelengths. From a fundamental viewpoint, the fact that broadening with a quasi-CW pump leads to the excitation of a very large number of solitons has meant that the effects of multiple soliton collisions and interactions are receiving renewed attention [26, 27]. In particular, recent theoretical studies suggest that new insights can be attained by adapting research from complex systems, turbulence and thermodynamics. Indeed the first publications using these ideas are beginning to appear [28, 29].

Figure 2 uses results from numerical simulations to illustrate some of these novel features of supercontinuum dynamics in the quasi-CW and long pulse regimes. Figure 2(a) uses the time-frequency spectrogram representation to show the complex evolution of a noise-seeded supercontinuum at various stages and the emergence of a large number of solitons on the long wavelength edge of the pump. Understanding the collective dynamics of these solitons remains an important open area of research. In this context, Figure 2(b) shows results from stochastic simulations of picosecond supercontinuum generation, superposing output spectra (gray curves)
from 1000 simulations as well as the calculated mean (black line). The expanded view of the long wavelength edge shows how a small number of solitons undergo an increased red shift relative to the mean, representing the tail of a characteristic “L-shaped” probability distribution [20]. It is the statistical analysis and distribution fitting of the amplitudes of these solitons in the tail that can reveal extreme value or “rogue” characteristics. Soliton interactions and collisions appear also to play an important role in the dynamics that generate these particular events.

Hollow-core nonlinearities

Another PCF milestone celebrating its tenth anniversary in 2009 is photonic bandgap guidance in a hollow core (HC) structure [30]. When compared to solid core fibre, HC-PCF exploits a fundamentally different type of guidance, confining light to a low-index region by a two-dimensional photonic bandgap crystal. In the context of nonlinear optics, a unique feature of the HC-PCF is that it can be applied at both ends of the nonlinear spectrum – when filled with air, low intrinsic nonlinearity enables high power pulse delivery applications, whilst when filled with appropriate gas and liquid phase media, high intrinsic nonlinearity enables the observation of frequency conversion effects at very low power levels.

More specifically, in the case of air-filled HC-PCF, the effective nonlinearity is reduced by as much as three orders of magnitude when compared to solid core fibres. But since the overall dispersion is generally anomalous over the majority of the transmission profile, guidance of high peak power pulses via nonlinear soliton effects is nonetheless possible. In a 3 m long air-filled fibre, Ouzonov et al. demonstrated guidance of 2.4 MW solitons of 110 fs duration around 1500 nm, but the Raman self frequency shift in air ultimately shifted the solitons towards the absorbing edge of the bandgap. However, using Raman-inactive Xe gas, this effect could be
avoided and the propagation of 75 fs pulses at 5.5 MW was reported [31]. These results have motivated a number of other exploratory studies in the ultrafast optics and source development field. A natural follow-up has been higher-order soliton compression again in Xe [32] whilst other studies have used HC-PCF in the construction of all-fibre format chirped pulse amplifier systems operating with kW peak powers [33]. In this latter parameter regime, propagation exploits the ultra-low nonlinearity of the HC-PCF to obtain purely dispersive recompression of high power amplified pulses from compact fiber systems. Although subsequent development has allowed increased power scaling of these systems, it is unlikely that the all-fibre systems will be able to match the ultimate power performance of optimized bulk systems. Nonetheless for applications where footprint and robustness are paramount, such systems remain commercially attractive.

An important area where HC-PCF finds unique application is through filling the hollow core with a non linear material such as gas or liquid. Bandgap guidance of light in the core then allows greatly enhanced interaction lengths such that nonlinear effects can be observed at much reduced power levels. This potential for ultralow power gas-phase nonlinear optics has been beautifully demonstrated in a series of experiments by Benabid et al., where stimulated Raman scattering in H₂-filled fibres was reported with thresholds up to $10^6$ times lower than in the bulk configuration [34]. A particularly elegant demonstration of the unique advantages of HC-PCF for nonlinear optics was the use of the photonic band gap structure as a filter in such experiments, selectively allowing operation on the weaker rotational Raman bands by filtering and consequently suppressing vibrational stimulated Raman scattering [35].

Another nonlinear process that has been studied at ultralow power levels in HC-PCF is electromagnetically induced transparency (EIT), with experiments in acetylene providing proof-
of-principle results in the telecommunications wavelength band [36, 37]. These results may point to future application in quantum information technologies. Other recent applications of HC-PCF include the generation and guidance of multi-octave frequency combs [38] and the report of sub watt CW pumped Raman laser action with bulk optical coupled end mirrors [39]. Of course, the selective filling of HC-PCF for nonlinear optics is not restricted to gases – liquids can also provide nonlinear responses that can be exploited for frequency conversion. Indeed, some recent results have used an appropriate water-filled HC-PCF pumped by a high power 980 nm source for supercontinuum generation [40].

Figure 3 presents a selection of these results, illustrating the tremendous potential of HC-PCF as an enabling technology for future research in different areas of nonlinear optics. In the future, the high efficiency of stimulated Raman scattering in hydrogen and other gases may lead to compact sources for the generation of sub cycle optical pulses for attoscience applications. In this regard it is important to note that work is also underway to integrate HC-PCF nonlinear devices with more conventional solid-state technologies. Important practical developments include photonic microcells where HC-PCF are hermetically sealed to solid conventional optical fiber, and the use of femtosecond micromachining to yield additional functionalities [41, 42].

**Draw-tower tapering**

An important recent advance in PCF fabrication has been the report of controlled tapering during the draw tower phase. In particular, by varying the fibre drawing parameters, it is now possible to realize custom tapered PCF with dispersion and nonlinearity parameters that can vary longitudinally on length scales of 10’s of meters. Significantly, this technology has been demonstrated with both solid core and hollow core PCF, and tapered fibres of both types have
found immediate application in pulse compression. This work has built on the well-established physics of soliton propagation in dispersion-decreasing fibre (DDF) to develop tapered-PCF designs optimized for the compression of pJ energy picosecond pulses around 1 μm to the ~50 fs regime [43]. As with any soliton-based technique, there are tradeoffs between fibre dispersion and pulse energy. Nonetheless, compression of pulses with pulse energies greater than 50 nJ at 800 nm has been possible using tapered hollow core PCF [44]. The possibility to perform custom tapering of HC-PCF in this way raises the possibility of simultaneous high power delivery and compression whilst in the case of solid core PCF, perhaps the most exciting future prospect involves the fabrication of precisely designed longitudinal dispersion and/or nonlinearity maps for controlled spectral broadening under general conditions [45].

Figure 4 highlights the potential of this technology, showing the vast dispersion and nonlinearity parameter space possible with control of PCF dimensions [(a) and (b)] and results of soliton compression where a 15 fold reduction in pulse duration has been observed [(c) and (d)]. Interestingly, when combined with a convex dispersion profile, DDF propagation can lead to highly uniform and stable supercontinuum generation, and numerical studies extending ideas originally developed for telecommunications spectral slicing have recently explored this possibility with PCF [46]. Experiments in this area would represent a logical next step.

**Emerging nonlinear waveguides**

Initial studies of nonlinearity in PCF focused on silica-based fibres, highlighting the unprecedented degree to which the nonlinear and dispersive properties could be engineered through waveguide design. Some of the most exciting recent work in this field has now applied
these ideas to non-silica glass fibres and planar waveguides, promising the development of a new generation of nonlinear waveguide structure.

The nonlinear response of a waveguide $\gamma = n_2\omega/cA_{\text{eff}}$ can be tailored in two ways: through material selection to modify the nonlinear refractive index $n_2$; and waveguide design such that the modal effective area $A_{\text{eff}}$ optimizes the nonlinear interaction. One approach to developing PCF with higher nonlinearities has been to use non-silica “compound” glasses, because their higher linear refractive indices leads to increased modal confinement and their associated nonlinear refractive indices can be enhanced by orders of magnitude relative to silica [47]. They are also attractive for applications at infrared wavelengths when losses in fused silica can become detrimental. A wide range of studies using PCF based on lead-silicate, bismuth and tellurite glasses have been carried out [48], and a particularly impressive recent result has been the observation of supercontinuum generation in a tellurite PCF out to near 5 μm [49]. Interestingly parallel work using non-PCF Fluoride fibre has achieved similarly impressive results, reporting a high power system with more that 1 W average power extending to 4 μm [50]. In fact, these results provide a very nice example of the recent synergy that has developed between research using both conventional fibres and PCF. Another approach has been to start from standard silica-based PCF, but to use post-tapering (e.g. using a flame-brush technique) to increase the effective nonlinear response by reducing the fibre dimensions to the sub-micron level. In such tapered fused silica “nanowires”, both supercontinuum generation and soliton compression have been reported [8].

For applications where the integration potential for telecommunications applications is critical, the ideas of dispersion and nonlinearity engineering from PCF research have been used to optimize the design of waveguides in materials such as silicon and chalcogenide glass.
Experimental results studying supercontinuum generation and other nonlinear frequency conversion processes have been obtained, and may point to a new class of nonlinear photonic device for future signal processing applications [51-53]. The study of nonlinear propagation in these new waveguides is also of interest from a theoretical perspective and is stimulating research into developing new and more general nonlinear propagation models [54]. Another area of research into new materials is that of polymer PCF. Although not yet extensively studied for nonlinear applications, polymer fibres are nonetheless of much interest due to their potential for low cost production and their ability to yield transverse geometries difficult to realise in glass materials [47].

Old physics, new directions

Supercontinuum generation in photonic crystal fibres is a complex spectral broadening process that involves the interaction between a number of different nonlinear effects and the intrinsic linear dispersion of the fibre waveguide. Although many of these processes had been seen in the large number of experiments on nonlinear fibre optics carried out before 1999, the novel guidance properties of PCF made it particularly easy to generate octave spanning spectra. The use of PCF-supported supercontinuum generation found immediate application in frequency metrology, and also made it possible to study in detail previously-unappreciated aspects of complex nonlinear pulse propagation in optical fibres. Novel experiments using HC-PCF have taken gas and liquid-based nonlinear optics to a new regime and opened new and important interactions with other fields of ultrafast optics. These studies over the last 10 years have seen a remarkable number of developments by groups worldwide, and the quantitative agreement between intricate experiments and realistic numerical modelling is arguably as good as in any
other domain of modern physics. The use of PCF has reduced the power demands for the study of non linear optics, and this has both allowed technological developments to advance while also permitting fundamental studies to be undertaken with low power laser systems. At the same time, this research has resulted in the development of a number of unique and versatile instruments that have found commercial success, that continue to make significant contributions in fields ranging from precision frequency measurements to biomedical diagnostics.

Many challenges remain. In the case of solid core PCF, power scaling is a continual challenge, and will no doubt motivate continued work to design fibres with dispersion profiles tailored to available high-power pulsed sources. Generating shorter wavelength radiation in the UV and extended mid-infrared spectral broadening will also need addressing in the future, but the physics groundwork has been done and essentially this work will be technology driven. From a fundamental perspective, continuous wave supercontinuum generation may well provide an intriguing platform for the study of collective fibre soliton dynamics – the soliton gas – a regime of nonlinear optics that has not yet been amenable to widespread study. A challenge here will be to develop suitable measurement techniques for the study of intrinsically incoherent and noisy nonlinear optical processes.

When one considers the last 10 years of research in context, it becomes clear that PCF can be well-described as a unifying as well as an enabling technology. PCF appears as a common factor in groundbreaking experiments that have combined ideas and researchers from diverse domains such as guided wave and gas-based nonlinear optics, ultrafast source development, nanophotonics, materials science and clinical medicine. It is likely that dramatic progress will continue in all of these fields, but perhaps the most genuine future breakthroughs will be made with unexpected applications at the boundaries between disciplines. Another
important lesson to take from the last 10 years of PCF research is that a careful study of the literature can reveal previous studies in earlier systems that can provide both physical and time-saving insight into current experiments using more advanced technologies.

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**Competing Financial Interests**

The authors declare that there are no competing financial interests in this work.
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Figure Captions

Figure 1  **Dramatic frequency conversion can also be seen in non-supercontinuum experiments.** Complementing the now-ubiquitous images of supercontinuum generation in PCF, this figure shows recent results reporting tunable narrowband spectral generation from a picosecond PCF optical parametric oscillator. The photograph and tuning curve in (a) and (b) respectively show the dramatic tuning characteristics spanning the visible spectral range, whilst (c) illustrates the simplicity of the butt-coupled OPO cavity. Results adapted from Ref. [15].

Figure 2  **Current research into supercontinuum dynamics is tending to focus on novel features of the quasi-CW or long pulse regime.** (a) Simulated spectrogram evolution for a high power quasi-CW pumped supercontinuum using 170 W pump power and near zero dispersion wavelength pumping. Following modulational instability, inspection shows soliton-dispersive wave trapping after 9 m and a clear one-to-one correspondence between soliton-dispersive wave components after 25 m [25]. (b) Results from 1000 simulations of picosecond pumped supercontinuum generation seeded from noise showing a long tail of red-shifted soliton pulses in the expanded subfigure of the long wavelength edge [21].

Figure 3  **HC-PCF enables the study of diverse nonlinear effects in gases and liquids.** (a) Resonant EIT in acetylene using a 1.3 m PCF segment. In the absence of a control, tuning the probe yields Doppler broadened absorption, whereas the presence of a 320 mW control beam yields EIT. (Black: theory; Gray: experiment) [36]. (b) Generation of an octave-spanning frequency comb in Kagome HC-PFC (inset) through stimulated Raman scattering in molecular hydrogen [38]. (c) Supercontinuum generation in a 5 cm water-filled HC-PCF (inset) at peak powers shown. Pump wavelength is 980 nm and the zero dispersion wavelength is ~ 1 μm [40].
Figure 4  Draw-tower tapering allows fabrication of longitudinally-varying dispersion and nonlinearity profiles, opening new possibilities for nonlinear optics in PCF. For the structure in (a), the contours in (b) show variation in dispersion (red) and effective area (blue) as a function of pitch \( \Lambda \) and air fill fraction \( d/\Lambda \) [45]. Adiabatic soliton compression can be observed in PCF where the structure varies longitudinally as in (c). For dispersion varying from 33 ps/nm km to 5 ps/nm km at 1.06 \( \mu \)m, changing pulse energy optimizes compression. Minimum durations of 48 fs are obtained, with the interferometric autocorrelation (inset) confirming the compressed pulse quality [43].
Figure 1
Figure 2
Figure 3
Figure 4