Understanding of supercontinuum generation and nonlinear fiber optics in microstructure fiber has enjoyed a spectacular decade of progress.

The 2009 Nobel Prize award to Charles Kao has once again highlighted the impact of low-loss optical fibers on modern technology. Although Nobel Prizes sometimes recognize fields that have reached technical saturation, nothing could be further from the truth in the case of fiber optics. Research into both fundamentals and applications remains as dynamic as ever, and new results continue to open up unexpected directions of study.

In very large part, this has been due to the development of the photonic crystal fiber (PCF) in the 1990s, and the revolutionary experiments on white light supercontinuum generation reported from Bell Labs in the January 2000 issue of the journal Optics Letters (see Figure 1).¹ The fiber used in these experiments consisted of a solid silica core surrounded by a periodic array of air holes. This class of PCF guides light by means of total internal reflection, but optimizing the air-hole geometry provides degrees of freedom that are unattainable in conventional fiber.² In particular, it is possible to tailor the dispersive and nonlinear fiber properties to specific applications and sources. Indeed, it was matching the zero-dispersion wavelength of the Bell Labs PCF to the operating wavelength of the femtosecond titanium sapphire laser that was the key factor in obtaining such efficient spectral broadening. Using only 75cm length of PCF, the group of Ranka was able to generate a white-light supercontinuum spanning an octave of bandwidth. This result has fundamentally altered the research landscape in nonlinear fiber optics.

Nonlinear spectral broadening had, of course, been the subject of much previous study in conventional fiber, but the generation of such broad bandwidth in PCF through the combination of multiple nonlinear interactions led to significant additional complexity. It thus took some time before researchers developed a comprehensive physical picture deconstructing the contributing processes. Our own work in this area focused on understanding the stability and noise properties of the supercontinuum, and synthesizing the vast existing literature in this field across different areas of optics in a way that was accessible and useful to the fiber-optics community.³ Even before full theoretical models were developed, one thing that was clear from the outset was the potential of PCF supercontinuum to revolutionize the field of optical frequency metrology. The key technical aspect here was the fact that an octave-spanning optical field could be used to self-reference a frequency comb from a low-power mode-locked laser. This yielded a simple and compact device for absolute frequency measurements that could completely replace the existing technology of frequency chains that typically take up a large laboratory.⁴

Such precision measurements have had very important and wide implications—from testing the fundamental theories of physics, to improving high-bit-rate telecommunications—and the fiber-based frequency comb played a part in another Nobel

Figure 1. After ten years, generating a supercontinuum in the laboratory is as impressive and exciting as ever, and detailed study of the physics and applications continues to raise new questions and point to novel applications.

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Prize, this time in 2005 for Hall and Hänsch. The high brightness and broad bandwidth of the white-light supercontinuum have found many applications in other areas of optics such as spectroscopy, microscopy, and high-power fiber-format source development. A number of companies now market compact broadband sources exploiting the physics of supercontinuum generation in PCF and other classes of dispersion-engineered fiber. The possibility to engineer the dispersion of PCFs has also led them to be applied in the development of tunable narrowband sources based on novel phase-matching mechanisms for optical parametric oscillation.

From a fundamental viewpoint, research into the mechanisms of supercontinuum broadening has led to improved insight into the field of nonlinear optics in general and some unexpected analogies with other areas of physics. Cross-phase modulation effects spanning the entire supercontinuum bandwidth have been interpreted in terms of an analogy with gravity, and the intriguing possibility of generating laboratory-scale black holes has been raised. Studies of the noise properties of the supercontinuum have shown that certain types of spectral fluctuation can be interpreted as a form of optical ‘freak wave,’ with intriguing links to develop an improved understanding of the infamous and destructive large-amplitude waves observed on the surface of the ocean.

The success of waveguide engineering in silica-based fibers has been accompanied by parallel efforts to engineer nonlinear devices using materials such as chalcogenide and silicon with particular promise for photonic integration. Research has also considered nonlinear propagation in hollow-core PCF. A unique feature of this class of fiber is that it can be applied at both ends of the nonlinear spectrum: when filled with air, low intrinsic nonlinearity enables distortion-free high-power pulse delivery, while when filled with appropriate gas or liquid, the intrinsically high material nonlinearity enables the observation of frequency conversion effects at very low power levels. Hollow-core PCF offers tremendous possibilities to develop a new generation of compact gas-filled fiber devices, as resonant nonlinearities exhibit many unique properties based on coherent light-matter interaction that may lead to entirely new functionalities that have simply not been considered practical before.

It is very safe to say that last decade of research in fiber optics has been dominated by PCF physics and applications. PCF appears in many truly breakthrough experiments that have combined ideas from different research areas such as guided wave nonlinear optics, source development, nanophotonics, materials science, and biology. Significantly, the fiber technology itself is becoming more routine and widely available, so there is every reason to believe that this field will continue to develop even further.

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References