


# Specialty Photonic Crystal Fibers and Their Applications

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This year not only commemorates the 60th anniversary of nonlinear optics with the seminal experiment of second harmonic generation [1], but it is also the 30th anniversary of the invention of the photonic crystal fiber (PCF) [2]. Following their first practical demonstration in 1996 [3], PCFs [4,5] have rapidly evolved into an established platform for applications in both academic and industrial environments. Their unique ability to confine light in a far more versatile way than possible with conventional optical fibers facilitated the expansion of the multifaceted world of PCF to cover not only nonlinear optics [6], but also many other disparate fields such as interferometry [7], beam delivery [8], laser science [9], telecommunications [10], quantum optics [11], sensing [12,13], microscopy [14], and many others.

More recently, there has been a great interest in the design, fabrication, and application of specialty PCFs with otherwise inaccessible and exotic properties far beyond the capabilities of standard fibers. These include, but are not limited to, the close-to-real fulfilment of the long-standing dream of lowering the minimum attenuation achievable in current fibers for communications [15], the use of glasses other than silica to manufacture PCFs with an enhanced performance in originally forbidden spectral regions such as the ultraviolet (UV) [16] or the mid-infrared (MIR) [17], or the three-dimensional engineering of fibers to open new horizons in fundamental science [18,19]. Furthermore, specialty PCFs have also jumped into real-world applications, playing a key role in the development of, e.g., the new generation of high-power fiber lasers [20] or constituting a new paradigm in photochemistry [21,22].

This special issue in *Crystals* is intended to provide an overview of the state-of-the-art in specialty PCF technology and its multiple applications, combined with an optimistic outlook to what lies ahead. It comprises six original research papers and one review from different leading research institutions worldwide.

The review *Application of Hollow-Core Photonic Crystal Fibers in Gas Raman Lasers Operating at 1.7  $\mu\text{m}$*  [23] by the Changsha Environmental Protection Vocational College, the National University of Defense Technology, and the State Key Laboratory of Pulsed Power Laser Technology (China) focuses on the detailed description of the origin and development of near-infrared narrowband pulsed laser sources based on stimulated Raman scattering in gas-filled hollow-core PCFs. It includes a thorough revision of the literature on this technology, which has successfully been applied through the years in many spectral regions from the UV [24,25] to the visible [26,27] and infrared [28,29]. In addition, the research paper *Hydrogen Molecules Rotational Stimulated Raman Scattering in All-Fiber Cavity Based on Hollow-Core Photonic Crystal Fibers* [30] by the same group reports on the implementation of a laser cavity to enhance rotational SRS in a hydrogen-filled hollow-core PCF.

The original research paper *Geometrical Scaling of Antiresonant Hollow-Core Fibers for Mid-Infrared Beam Delivery* [31] by the Nanyang Technological University (Singapore) reports



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a detailed theoretical analysis of the influence of the structural parameters on the MIR performance of novel anti-resonant hollow-core fibers. Interestingly, a resonant-like coupling between core modes and modes localized in the glass capillary walls is predicted to occur in the long-wavelength edge of the fundamental transmission band [32], which might have practical implications on the generation and guidance of MIR light. In this regard, chalcogenide glasses are particularly attractive as they present a very broad MIR transmission window extended up to 18  $\mu\text{m}$ , thereby covering the so-called “molecular fingerprinting” region, of crucial importance in spectroscopic and defense applications. Therefore, the paper from NTU Singapore is perfectly complemented by the original research work presented by the *University of Rennes* and the *University of Aix-Marseille* (France). In their joint paper, they present an *Investigation on Chalcogenide Glass Additive Manufacturing for Shaping Mid-Infrared Optical Components and Microstructured Optical Fibers* [33]. An initial step, presented here, is to identify a glass that is suitable for 3D printing. The preform of anti-resonant hollow-core fibers is then printed and subsequently drawn into a fiber. An important aspect presented in this work is that the printing process does not seem to affect the properties of the glass itself. Although imperfections in the printing procedure can however yield additional losses, the presented work certainly shows the potential of the approach, which would greatly ease the fabrication of complex micro-structures.

Specialty PCFs are excellent vehicles for the spectral broadening of a pump laser by exploiting the delicate interplay of third-order nonlinear effects with a tailored dispersion landscape. More recently, the investigation of the polarization properties of these broadband sources [34] has attracted significant attention because of their potential use in spectroscopy [35]. As it is often the case in nonlinear optics, dispersion management holds the key to efficiency, and even gas-filled hollow-core PCFs can yield extremely broad supercontinua [36,37] despite their weak nonlinear material response. In particular, by filling a broadband-guiding hollow-core PCF with noble gases and pumping it with near-infrared ultrashort pulses, it is possible to generate tunable UV radiation via soliton self-compression [38] and resonant dispersive wave emission [39,40]. The original research paper *Photoionization-Induced Broadband Dispersive Wave Generated in an Ar-Filled Hollow-Core Photonic Crystal Fiber* [41] by the *State Key Laboratory of High-Field Laser Physics* and *CAS Center for Excellence in Ultra-Intense Laser Science*, the *Center of Materials Science and Optoelectronics Engineering*, and the *R&D Center of High Power Laser Components* (China) reports on the experimental observation of the spectral broadening of multi-peaked UV dispersive waves via plasma-induced soliton blue-shifting. When the intensities attained upon temporal self-compression of the pump pulses are high enough to cause partial strong-field ionization of the gaseous core, the resulting free-electron cloud strongly modifies the dispersion landscape and affects the nonlinear propagation dynamics [42,43]. This effect is enhanced when the UV emission matches the high-loss bands of the fiber [44].

By contrast with the pressurization of a hollow-core PCF with gas to adjust the dispersion, filling the air channels of a standard solid-core PCF guiding light by modified total internal reflection can drastically affect its guidance mechanism. For example, an endlessly single-mode solid-core PCF can then be turned into a photonic bandgap fiber [45]. In their research paper *Understanding Nonlinear Pulse Propagation in Liquid Strand-Based Photonic Bandgap Fibers* [46], a team from the *University of Jena* (Germany) explores the effects of injecting liquid carbon disulfide ( $\text{CS}_2$ ) in the air channels of a silica-made PCF on the guidance and nonlinear properties of the resulting hybrid fiber, which exhibits distinct transmission bands as previously shown in photonic bandgap fibers [47]. They then generate broad supercontinua in the  $\text{CS}_2$ -filled fiber, reporting a strong influence of the location of the pump wavelength with respect to the band edge on the dynamics.

Another application of the third-order nonlinearity is the development of sources based on four-wave mixing yielding discrete sidebands, with applications in, e.g., quantum optics. The original research paper *Polarization modulation instability in dispersion-engineered photonic crystal fibers* [48] by the *Universidad de Valencia* (Spain) reports the use of various liquids to fill the air channels of a solid-core PCF to achieve specific conditions, such as an

optimal dispersion landscape, for the observation of sidebands created through polarization modulation instability. The thorough experimental demonstration of the phenomenon is supplemented by a rigorous theoretical description providing a solid understanding of the results.

In summary, this special issue showcases the widespread interest that specialty PCF technology still sparks 30 years after its inception. Owing to their current level of maturity and multidisciplinary nature, specialty PCFs are expected to play a key role in multiple scientific, industrial and societal advances in the years to come.

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