Photonic crystal fibers for supercontinuum generation

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Abstract Photonic crystal fibers (PCFs) present a wavelength-scale periodic microstructure along their length. Their core and two-dimensional photonic crystal might be based on varied geometries and materials, allowing supercontinuum (SC) generation due to nonlinear effects in an extremely large wavelength range. In this paper we have reviewed PCFs utilized for SC generation. Fiber fabrication for SC generation is present. Spectral broadening mechanisms are also described in brief. Particular attention is as well as paid to PCFs including uniform PCFs, cascaded fibers, tapered fibers and PCFs with special material doped, which are commonly used to generate SC.

Keywords photonic crystal fibers (PCFs), supercontinuum (SC), PCF fabrication, nonlinear optics, tapered PCF, cascaded PCF, Ge-doped core

1 Introduction

Supercontinuum (SC) generation has attracted much attention since it was first reported in 1970 by Alfano and Shapiro [1–3]. They observed the generation of a white light spectrum covering the entire visible range from 400 to 700 nm after propagating picosecond pulses at 530 nm. Bulk borosilicate glass was used as a nonlinear medium in the pioneering work [1]. SC generation in optical fibers was first observed in 1976 by Lin and Stolen for pumping in the normal group velocity dispersion (GVD) regime of standard silica fiber [2]. Philip Russell, the inventor of photonic crystal fibers (PCF) technology, worked on PCFs from 2001, realizing the renaissance of interest in optical fibers and their uses. His work marked the start of a new era in SC generation in PCFs [3]. In the 20th century PCFs gradually make a great difference to efficient octave-spanning SC. It has been a subject of intense research since Ranka reported an optical continuum 550 THz in width, extending from the violet to the infrared, by propagating pulses of 100 fs duration and kilowatt peak powers through a PCF near zero-dispersion wavelength (ZDW) [4]. The nonlinear effects responsible for the spectral broadening require a high light intensity. It is spatial nonlinear effects resulting in self-focusing of the beam that closely connect with SC generation in bulk glass. In contrast, PCFs who have subtle variations in the refractive index can tightly confine the beam in a small core. Thus, it is to a large degree possible to engineer the dispersion of PCF by proper design of the structural parameters and high beam intensity can be sustained over larger propagation distances. This reduces the requirement of high laser power for efficient broadband generation [5]. In parallel with these developments, the availability of PCF was leading to a dramatic revolution in the broad spectra’s realized and potential applications. The SC spectrum is not only broad, but is also spatially coherent, contrary to light from, e.g., a tungsten lamp, and consequently has higher brightness. These properties has opened up new applications in fields such as optical frequency metrology, optical coherence tomography, pulse compression, chemical and bio-medical system, modern military, space industry, etc. [2].

2 PCFs fabrication

Solid core PCFs have been in practical existence as low-loss waveguides since early 1996 [6]. The initial demonstration took four years of technological development, and since then, the fabrication techniques have become more and more sophisticated [7]. Generally, PCF are fabricated by the conventional stack-and-draw technique as displayed in Fig. 1. Silica capillaries with given outer diameter and inner diameter are stacked together to form an ideal hexagonal structure with perfect regularity, air holes embedding within a pure silica fiber strand. The stack is bound with wire before being inserted into a jacketing tube, and the whole assembly is then mounted in perform feed unit (it is usually called drawing tower) for
drawing down to fiber. During the fiber drawing, the overpressure applied into the holes should be specially controlled to achieve the inflation of air holes [8]. Judicious use of pressure and vacuum allows some limited control over the final structural parameters, for example, the $d/A$ value [7].

### 3 Spectral broadening mechanisms

As is well established, effects such as self-phase module (SPM), four wave mixing (FWM), soliton self-frequency shift (SSFS), the generation of dispersion wave and cross phase module (XPM) should be responsible for the SC generation. When pumping using femtosecond pulses in the anomalous GVD regime of the fiber, SC generation is dominated by soliton-related propagation effects. The most importance of these in the initial stages is the soliton fission process, whereby a pulse with sufficient peak power to constitute a higher-order soliton is perturbed and breaks up into a series of lower-amplitude sub-pulses. Each of these pulses is, in fact, a constituent fundamental soliton. The process is followed by the Raman shifting of constituent ejected solitons and the associated generation of dispersive waves from each ejected fundamental soliton due to the effect of higher-order dispersion. It is the phase-matching condition that determines the spectral position of dispersive wave [1]. Afterwards, the soliton self-frequency shift extends the broadening to the infrared side of the spectrum while trapped dispersive waves into short-wavelength region [3]. SC generation with long pulses in the anomalous GVD regime involves similar soliton-related dynamics as in the femtosecond regime. However, in contrast to the femtosecond case, solitons play a relatively minor role during the first step of propagation. Recent numerical studies by Travers et al. [9,10], Mussot et al. [11] and Cumberland et al. [12] have provided further insight into this dynamics, and explicitly demonstrated that four-wave mixing and/or Raman scattering dominate the initial steps of SC generation with long pulses, leading to symmetrical broadening of the pump spectrum. Subsequent soliton formation and breakup which are subject to the peak power and dispersion values takes place, and Raman self-scattering can then lead to a long-wavelength soliton continuum [10,13].

### 4 PCFs utilized to generate SC

In this section, we provide an overview of the PCFs of two types to generate SC. One type of PCFs has changes in geometry. Uniform PCFs, tapered fibers and cascaded fibers are included. While the other type of PCFs is modulated in material. Doping material like germanium or fluorine, even water is used in the central rod to modulate the PCF’s dispersion and nonlinear properties.

#### 4.1 PCFs with different geometry

Uniform PCFs may be the most conventional optical fiber and has attracted much attention. Ranka et al. [4] generated an ultrabroadband continuum extending from 390 to 1600 nm by injecting pulses of 100 fs duration, 800 pJ energy, and a center wavelength of 790 nm into a 75 cm section of fiber in 2000. Here the combined nonliner effects including self-phase modulation, soliton propagation, efficient four-wave mixing and Raman scattering result in a broad, flat spectrum. In 2002, Dudley et al. [14] studied the generation of SC in these fibers. In the femtosecond experiments, a continuum from 450 to 1250 nm has been generated in a 1 m length of fiber pumped at 780 nm by 100 fs pulses from a Kerr-lens model-locked Ti: sapphire laser.

In 2008, the work by Mussot et al. provided a comprehensive description of the dynamics involved [11]. They used a randomly polarized CW Yb fiber laser with 12 W and spectral width of 1 nm, centered at 1066 nm. By injecting 6 W inside 500 m long PCF, they