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Numerical simulation of supercontinuum generation in liquid-filled photonic crystal fibers with a normal flat dispersion profile

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ABSTRACT

A photonic crystal fiber (PCF) filled with commercial index-matching liquids is designed to control the dispersion properties of PCF. Numerical simulation of supercontinuum (SC) generation in these liquid-filled PCFs is then conducted at a temperature of 25 °C. The definition of spectral flatness measure (SFM) is introduced to quantitatively describe the SC flatness. Numerical simulations are performed to study the propagation of femtosecond pulse in the liquid-filled PCFs. Results show that using the index-matching liquids in PCF, the dispersion properties of the PCF can be easily engineered without changing in the geometry. Simulations also show that 50 fs pulses with a center wavelength of 1060 nm generate relatively flat SC spectra in the 25 cm-long PCF with two Oil2-filled rings. With an applied pump power of 24 kW, a flat (SFM = 0.9670) spectral bandwidth of 700 nm (900–1400 nm) is achieved. Results further demonstrate that using index-matching liquids to fill the PCF inner ring can exactly control its dispersion properties and generate a flat SC spectrum in the specified wavelength region.

1. Introduction

Supercontinuum (SC) generation has become an active research topic over the last few years [1–9] because of its unique application in diverse fields, such as in optical coherence tomography, fluorescence microscopy, flow cytometer, characterization of optical devices, generation of multiple carrier waves in optical fiber communications systems, and measurement of the carrier-envelope offset frequency of frequency combs. Photonic crystal fibers (PCF) that is also called as holey fiber, hole-assisted fiber, or microstructured fiber are the medium of choice for SC generation in optical fibers because of the design flexibilities in its dispersion and nonlinear properties [10–17]. According to its zero-dispersion wavelength (ZDW) properties, PCF can be classified into three basic types [18], namely, single ZDW PCFs, two ZDWs PCFs, and all normal dispersion PCFs.

After extensive experiments and theoretical studies [18–20], SC generated in single ZDW PCF relies on soliton dynamics when pumped in the anomalous dispersion regime. The drawback of utilizing soliton dynamics for SC generation is the occurrence of soliton fission that splits up the input pulse into a series of subsequent soliton pulses, each exhibiting unique temporal and spectral distributions that are highly susceptible to pump pulse shot noise. Recently, SC generation in two ZDWs PCF and all normal dispersion PCF has become an attractive topic because of the intrinsic coherent properties.

The suppression of soliton fission centered near the pump in PCF with two closely spaced ZDWs is an approach to achieve SC spectra [21–26]. In PCFs owning two ZDWs, two dispersive waves can be generated because of the impact of self-phase modulation (SPM) and soliton self-frequency shift process, which is a disadvantage for generating uniform and smooth power spectral densities (PSD) across the SC [27,28]. On the other hand, SC generated using the approach has less useful spectral region [29] because of the lower PSD, although a wider spectrum is possible. After extensive studies, researchers are able to perform SC generation in all normal dispersion tapered suspended-core optical fibers [30]. When the pump wavelength lies in the normal dispersion regime (NDR), the noise sensitive effects are suppressed, resulting in excellent pulse-to-pulse coherence [18]. One difficulty in fabricating such small tapers is the collapse of the air holes. Although possible in principle, tapering the PCFs down to such small dimensions while preserving the cross-sectional structure is not trivial [31].

Therefore, researchers gained all normal dispersion PCF by changing the PCF designs (the pitch and air hole diameter). Based on all normal dispersion photonic crystal fibers (ANDi PCF), Heidt [5,18,30] conducted an experiment and theoretical investigation

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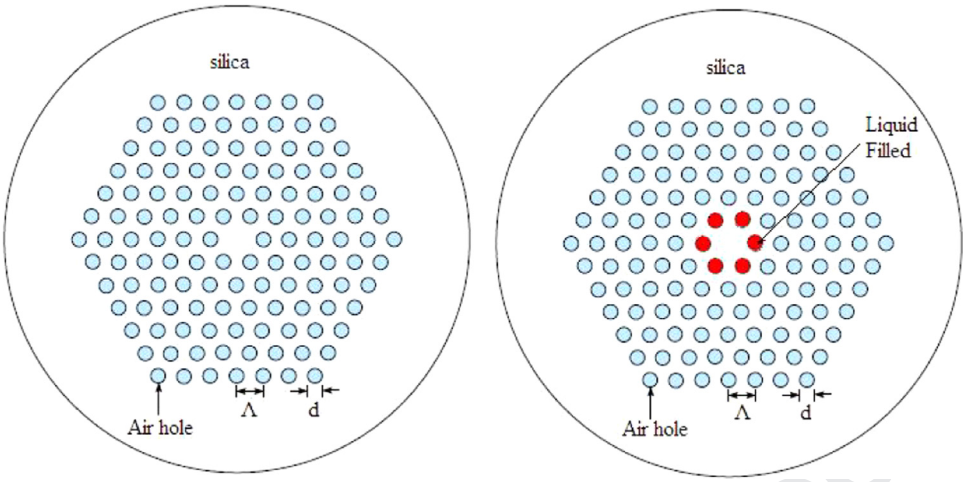

Fig. 1. Cross-sectional view of solid core PCF with triangular lattice, consisting six hexagonal rings of air holes. Left: Normal PCF ($\Lambda=2.1$ μm, $d=1.8$ μm); Right: PCF inner ring filled by liquid ($\Lambda=2.1$ μm, $d=1.8$ μm).

on the flatness of SC generated in the visible and near-infrared spectral regions. Yan [32] and Shuanglong [29] performed numerical simulation to study the smoothness and flatness of SC generated in microstructured optical fiber with all normal dispersion profile. Difficulty in controlling the accurate positions and radii of the air holes within a given PCF lattice should be noted. The broadening mechanism in ANDi PCF is dominated by SPM and optical wave breaking (OWB) [5]. Given that only the dispersion impact spectrum and no soliton is generated during the pump pulse transmission in the fiber, the breakup of the injected pulse into multiple pulses is suppressed and a single recompressible pulse remains in the time domain [18]. Hence, the generated SC could achieve flat and uniform spectrum of hundred nanometers. The approach with all its characteristics combined, and by changing the pump parameters could generate flat spectrum, however still requires changing in the PCF geometry. Therefore, ANDi PCFs are still not ideal candidates for specified SC applications.

Meanwhile, researchers found that to fill the PCF air hole with different liquids [10–13,15] can effectively control the dispersion properties of PCF. Marius Vieweg [33], Gerosa [34], and Gissibl [35] describe the manufacturing procedures for selectively closing holes in PCF and their infiltration with different liquids. A 3D direct laser-writing technique [36] is used to selectively seal single holes. Gundu [10] used an appropriate index-matching liquid to control the chromatic dispersion properties of PCF and gained an ultra-flattened dispersion in abnormal dispersion. Afterwards, different liquids [11,12,15,37–41], such as CS_2, nitrobenzene, toluene, chloroform, methanol, and water were used to fill the PCF (microstructured fibers or hollow core fibers) air hole, researchers then calculated dispersion properties and found that dispersion can shift from anomalous to normal dispersion at the pump wavelength, which is important for flat and smooth SC generation. In these cases the dispersion properties can be tailored by varying the core diameter or by the use of different liquids. Furthermore, investigations are carried out to demonstrate the possibility of changing the temperature to match the dispersion properties of selectively liquid-filled PCFs. [39] Pricking, [42] demonstrated that the retarded response of a nonlinear medium embedded in a single hole of PCF crucially affects the spectrum generated by ultrashort laser pulses. Ebnali-Heidari [43] proposed the use of optofluidic infiltration in PCF design to control dispersion properties in normal dispersion regions for flat SC generation. Maji [44] designed of all-normal and near zero flattened dispersion based on PCF using the selectively liquid infiltration technique.

Table 1
Cauchy equations of oils from Cargille laboratories [46].

Name	Cauchy equation (25 °C)	Temperatrue coefficient (dn_D/dt)
Oil1	$1.2955353+1.4884\times10^5/\lambda^2+2.155584\times10^{11}/\lambda^4$	-0.000333
Oil2	$1.343219+2.3702\times10^5/\lambda^2\text{-}5.438844\times10^{11}/\lambda^4$	-0.000339
Oil3	$1.387868+4.3418\times10^5/\lambda^2\text{-}4.474685\times10^{11}/\lambda^4$	-0.000412

In the present paper, we designed a PCF which is filled with commercial index-matching liquids to control the dispersion properties of PCF and we then conducted the numerical simulation of SC generation in liquid-filled PCFs. We used the spectral flatness measure (SFM) to quantitatively describe the flatness of SC. Initially, we employed finite element method (FEM) to design and optimize the liquid-filled PCF which dispersion curve is ultra-flattened near zero dispersion in NDR. Second, numerical simulations are performed by solving the generalized nonlinear Schrodinger Equation (GNLSE) with the adaptive split-step Fourier method (SSFM) to study the propagations of femtosecond laser pulse in the PCF. Finally, we introduced the concept of the SFM to quantitatively describe the flatness of SC. Based on the SFM, the flatness of SC are discussed. The influences related to the index of filled liquids, filled rings, and pulse parameters as well as peak power and pulse duration are analyzed in detailed. The simulation results demonstrate that using index-matching liquids to fill the inner ring of PCF can exactly control the dispersion properties and generate flat SC spectrum in specified wavelength region.

2. Theoretical model

Propagation and broadening of ultra-short pulses in fibers can be described by the GNLSE equation as below:

$$\frac{\partial A(z,T)}{\partial z}=\sum_{k\geq 2}\frac{i^{k+1}\beta_k}{k!}\frac{\partial^k A}{\partial T^k}+i\gamma\left(1+\frac{i}{\omega_0}\frac{\partial}{\partial T}\right)\times\left[A(z,T)\int_{-\infty}^{+\infty}R(T^{'})|A(z,T-T^{'})|^2dT^{'}\right]\tag{1}$$

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