Supercontinuum generation in ultra-flat near zero dispersion PCF with selective liquid infiltration

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A B S T R A C T

We present a new design study of ultra-flat near zero dispersion PCF with selectively liquid infiltration with all uniform air-holes in the cladding. The dependence of the individual parameters upon dispersion has been presented in detail. The study establishes that varying $d$ influences the total dispersion, whereas $\Delta$ has the desired effect of modifying the dispersion slope, and varying $n_L$ modifies both. With the above study we could achieve near zero ultra-flat dispersion as small as $0 \pm 0.41$ ps/nm/km for broad wavelength range of 452 nm. The optimized near zero ultra-flat dispersion PCF has been targeted for smooth and flat broadband spectrum supercontinuum generation (SCG) for near Infrared (IR) applications. Broadband SC generations corresponding to three different designs of ultra-flat dispersion fiber have been carried out by using picoseconds pulse laser around the first zero dispersion wavelengths (ZDW). The numerical results show that FWHM of around 400 nm with less than a meter long fiber can be achieved with these fibers that cover most of the communication wavelength bands. The proposed design study will be applicable for applications in the field of tomography, Dense Wavelength Division Multiplexing (DWDM) system, spectroscopy, etc.

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1. Introduction

Photonic crystal fiber (PCFs) [1,2], which enjoys some excellent properties like wide band single mode operation, great controllability over dispersion properties and higher nonlinearity, has been the target for various nonlinear applications like supercontinuum generation (SCG) [3], four-wave mixing [4] and parametric amplification [5] etc. The two key aspects for quality SC generation have been spectral width and flatness over broadband wavelength [3]. However, obtaining a relatively flat spectrum remains to be a challenge. To generate a flat broadened SC, high nonlinearity and flat chromatic dispersion are essential. This requirement can be met by optimizing the design of the fiber and the pumping condition. PCF can meet the demand for ultra-flat dispersion in the communication wavelength by its unique novel properties of dispersion tailoring and higher nonlinearity. However, the dispersion slope of such PCFs cannot be tailored for wide wavelength range with air-holes of same diameter. Various complicated designs such as different core geometries [6–8] and multiple air-hole diameter in different rings [7–12] have been studied to achieve ultra-flattened dispersion values over wider wavelength bandwidths. However, the technology of realizing complicated structures or PCF having air-holes of different diameters in microstructured cladding remains truly challenging. An alternative route of achieving similar performance is shown to be practicable by filling the air holes with liquid crystals [13,14] or by various liquids such as polymers [15], water [16] and ethanol [17]. Tunable PCF effect and long-period fiber grating has been successfully realized with liquid-filled PCFs [18].

In this work, we have successfully designed three ultra-flat near zero dispersion PCF with dispersion value as small as $0 \pm 0.41$ ps/nm/km with all equal air-hole diameters throughout the cladding that can be realized by standard fiber drawing technology. The air-hole diameter found to be in the range of $0.52–0.64 \mu m$ which can be fabricated easily as PCF with similar air-hole diameter has already been successfully realized [19]. The numerical studies show that the proposed fibers can generate around 400 nm of flattened broad band SC generation in the IR wavelength ranging from 1300 nm to 2100 nm.

2. Geometry of the studied structure and modal analysis

The schematic of the designed fiber has been shown in Fig. 1. The PCF used in our study is a triangular one with three numbers
of air-hole rings and the center air-hole ring is missing. The effect of variable air-hole diameter has been realized with the first air-hole ring is infiltrated with liquid of certain refractive indices (RI). The modal fields are calculated using CUDOS MOF Utilities [20] that simulates PCFs using the multipole method [21,22]. The numerical calculations namely dispersion parameter (\(D\)) and supercontinuum analysis are performed with MATLAB\textsuperscript{®}. The total dispersion (\(D\)) is computed with

\[
D = -\frac{\lambda}{c} \frac{d^2 \text{Re}[\varepsilon_{eff}]}{d\lambda^2}
\]

here \(\text{Re}[\varepsilon_{eff}]\) stands for the real part of the effective indices obtained from simulations and \(c\) is the velocity of light in vacuum.

3. Numerical results toward optimization for near zero ultra-flattened dispersion

Designing near zero ultra-flat dispersion for application like flat broadband spectrum in the communication wavelength has been a task with multi-dimensional parameter optimization which consists of liquid RI (\(n_L\)), hole to hole distance (\(\Lambda\)), and air-hole diameter (\(d\)). The optimization procedure had been trivial and it requires couple of steps, namely first studying the effect of the governing parameters upon dispersion. After studying the nature of the effect of the PCF parameters upon dispersion, we move to the next step of designing ultra-flat near zero dispersion with an artificial liquid (wavelength independent RI). The purpose of considering an artificial liquid initially has been to avoid the atrocious computation study of choosing a proper liquid out of so many available index matching liquids. In the final step, we choose available practical liquid with RI close to the previously obtained value, and optimize the other parameters to design the target of ultra-flat near zero dispersion PCFs.

The first step of optimization process has been presented in Figs. 2–4 where we have shown the effect of individual parameter upon total dispersion. Fig. 2 presents the effect of \(\Lambda\) upon \(D\), which clearly presents that the value of dispersion has changed because of change of \(\Lambda\) without much change in slope. So, varying \(\Lambda\) influences the total dispersion. Fig. 3 presents the effect of infiltrating RI of the liquid. Both the dispersion value and the slope changes for a change of \(n_L\). So, varying \(n_L\) modifies both the dispersion and its slope. The effect of air-hole filling fraction has been presented in Fig. 4. The figure clearly reveals that the slope of the dispersion changes drastically for a change of air-hole diameter. The effect can be understood based on the interplay between waveguide dispersion and material dispersion. For smaller \(d/\Lambda\), material dispersion dominates whereas the waveguide effect takes over for higher \(d/\Lambda\).

**Fig. 1.** Cross section of the proposed photonic crystal fiber. The shaded regions represent air holes infiltrated with liquid with refractive indices \(n_L\).

**Fig. 2.** Dispersion variation of the PCF as a function of \(\Lambda\) keeping \(n_L\) and \(d\) fixed.

**Fig. 3.** Dispersion performance as calculated for varying \(n_L\) values keeping pitch (\(\Lambda\)) and \(d\) fixed.

**Fig. 4.** Variation of dispersion as a function of air-hole diameter (\(d\)) with \(\Lambda\) and \(n_L\) remain constant.