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Near Zero Ultra-flat Dispersion PCF: Properties and Generation of Broadband Supercontinuum

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Abstract

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 towards achieving broadband supercontinuum generation (SCG). With rigorous series study of the optimization process we could achieve near zero ultra-flat dispersion as small as 0±0.41 *ps/nm/km* for broad wavelength range. 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 and spectroscopy applications etc.

Keywords

Microstructured Optical Fiber; Photonic Crystal Fiber; Ultra-flat Dispersion; Supercontinuum Generation

Introduction

Photonic crystal fiber (PCFs) [Broeng et al, 1999; Russel et al, 2006], 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) [Dudley et al, 2006;], four-wave mixing [Barh et al, 2013;] and parametric amplification [Chaudhari et al, 2012;] etc. The two key aspects for quality SC generation have been spectral width and flatness over broadband wavelength [Dudley et al, 2006;]. 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 the same diameter. Various complicated designs such as different core geometries [Hansen et al, 2003; Saitoh et al, 2006; Florous et al, 2006;] and multiple air-hole diameter in different rings [Saitoh et al, 2006; Florous et al, 2006; Saitoh et al, 2004; Saitoh et al, 2003; Poletti et al, 2005; Wu et al, 2005;] 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 [Zhang et al, 2005; Alkeskjold et al, 2006;] or by various liquids such as polymers [Eggleton et al, 2001;], water [Martelli et al, 2005;] and ethanol [Yiou et al, 2005;]. Tunable PCG effect and long-period fiber grating has been successfully realized with liquid-filled PCFs [Yu et al, 2009;].

In this work, we have successfully designed three ultra-flat near zero dispersion PCF with dispersion value as small as 0±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 μm to 0.64 μm which can be fabricated easily as PCF with similar air-hole diameter has already been successfully realized [Reeves et al, 2002;]. The numerical studies show that the proposed fibers can generate around 400nm of flattened broad band SC generation in the IR wavelength ranging from 1300 nm to 2100 nm.

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 that simulates PCFs using the multipole method [White et al, 2002; Kuhlmey et al, 2002;]. The numerical calculations namely dispersion parameter (*D*) and supercontinuum analysis are performed with MATLAB®. The total dispersion (*D*) is computed with

$$D = -\frac{\lambda}{c}\frac{d^2\,\mathrm{Re}[n_{eff}]}{d\lambda^2} \quad (1).$$

Here Re[n_{eff}] stands for the real part of the effective indices obtained from simulations and *c* is the velocity of light in vacuum.

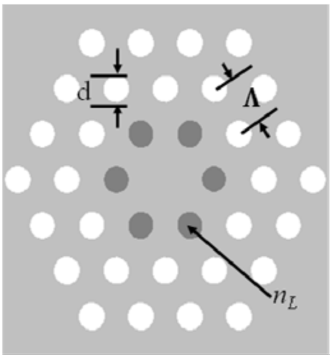

FIG 1: CROSS SECTION OF THE PROPOSED PHOTONIC CRYSTAL FIBER. THE SHADED REGIONS REPRESENT AIR HOLES INFILTRATED WITH LIQUID WITH REFRACTIVE INDICES N_L.

Numerical Results towards 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 (Λ), 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 moved to the next step of designing ultra-flat near zero dispersion with an artificial liquid (wavelength independent *RI*). In the final step, we chose available practical liquid with *RI* close to the previously obtained value, and optimized the other parameters to design the target of ultra-flat near zero dispersion PCFs. The detail procedure and the subsequent results are shown in detail in our previous studies [Maji et al, 2013]. In the above works, we have shown that, the effect of *varying the* Λ *influences the total dispersion*, whereas *d has the desired effect of modifying the dispersion slope*, and *varying* n_L *modifies both*. The issues related to the infiltration of the liquid into the air-holes (like whether the fluid wets glass and how viscous it is) are discussed in detail in the above work. With the help of the above works, we tried to develop our studies for relatively bigger air-holes for ease of fabrication.

To design the target of near zero ultra-flat near zero dispersion, we have considered few index matching liquids available with M/s Cargille Inc. USA. First of all, we selected one practical liquid (calling as liquid#1) whose *RI* is nearer to 1.340 around the communication wavelength range. The wavelength dependence of the liquid has been given through the Cauchy's formula in Eqn. (2). With this liquid, we have achieved near zero ultra-flat dispersion with 0±0.54 *ps/nm/km* from 1506 nm to 1934 nm *i.e.* for a wavelength range of 428 nm as demonstrated in Fig. 2 (with black line) with Λ=0.94 μm and *d*=0.52 μm. The value of first zero dispersion wavelength (*ZDW*) has been found out to be 1543 nm and the same has been mentioned with the vertical black dotted line in the figure. Total dispersion along with the contribution of the material dispersion of the liquid and background silica material dispersion towards the total dispersion has been shown in Fig. 3 for the above structure. The effect of liquid infiltration upon dispersion has been presented in Fig. 4. The figure clearly reveals the determining effect upon dispersion as the dispersion and the slope changes drastically with the introduction of the liquid in the air-hole rings. The flexibility of the design studies has been demonstrated by considering some other liquids which are having different *RI* than governed by Eqn. (2) as given in Eqn. (3) and Eqn. (4) for liquid#2 and liquid#3 respectively. With these liquids we tried to obtain different values of first ZDW such that the designs meet specific requirements for applications for different wavelength regions. An optimized design has been successfully demonstrated for a near zero ultra-flat dispersion with 0±0.41 *ps/nm/km* from 1580 nm to 2032 nm *i.e.* for a wavelength range of 452 nm as shown in Fig. 2 (with red line) with Λ=0.96 μm and *d*=0.55 μm and liquid#2. *ZDW* was found to be 1616 nm and the same has been revealed with the red dotted line. The last of the series has been achieved with *D* of 0±0.58 *ps/nm/km* from 1740 nm to 2200 nm *i.e.* for a wavelength range of 460 nm as demonstrated in Fig. 2 (with blue line) with Λ=1.02 μm, *d*=0.64 μm and liquid#3. The corresponding *ZDW* was found to be 1783 nm for this case and shown with the blue dotted line.

Cauchy equation of the liquids:

Liquid#1: $n1(\lambda)=1.3336794+219396/\lambda^2+3.562146\times10^9/\lambda^4$ (2)

Liquid#2: $n2(\lambda)=1.3289114+210577/\lambda^2+3.006168\times10^{10}/\lambda^4$ (3)

Liquid#3: $n3(\lambda)=1.3193754+192938/\lambda^2+8.306075\times10^{10}/\lambda^4$ (4)

where λ are in Angstrom.

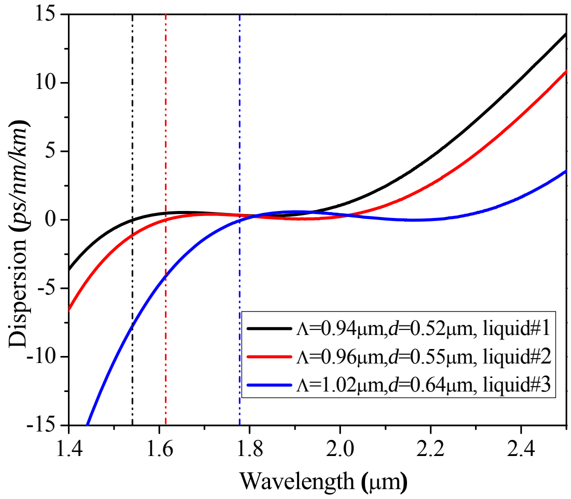

FIG 2: THREE OPTIMIZED ULTRA-FLAT DISPERSION PCF OBTAINED WITH THREE DIFFERENT LIQUIDS. THE VERTICAL DOTTED LINE PRESENTS THE WAVELENGTH CORRESPONDING TO FIRST ZDW WHICH ARE 1543nm, 1616nm and 1783nm OF THE THREE OPTIMIZED PCFS REPECTIVELY.

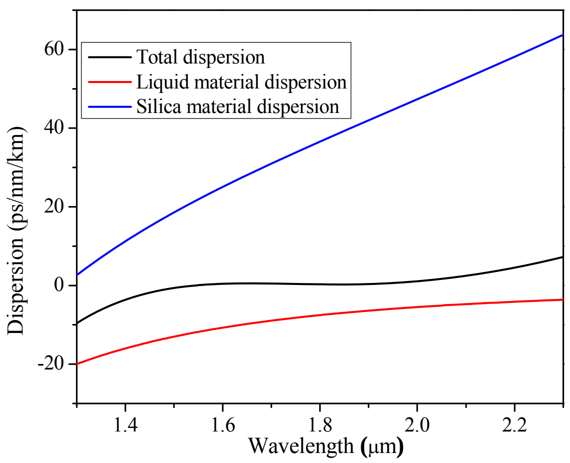

FIG. 3:THE CONTRIBUTION OF THE MATERIAL DISPERSION OF THE LIQUID AND BACKGROUND SILICA MATERIAL DISPERSION TOWARDS THE TOTAL DISPERSION.

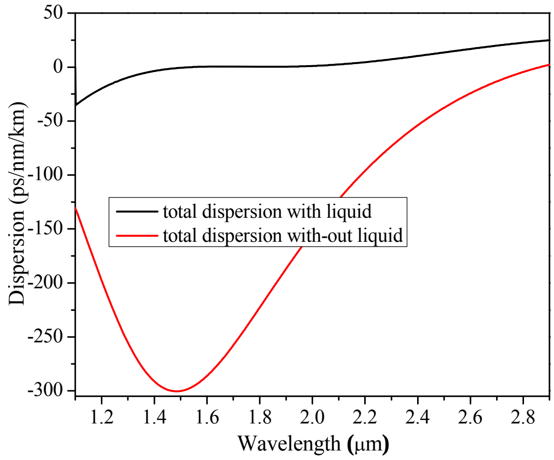

FIG. 4:THE EFFECT OF LIQUID INFILTRATION IN THE FIRST AIR-HOLE RING UPON DISPERSION. THE DISPERSION VALUES AND THE DISPERSION SLOPE OF THE GRAPH HAVE BEEN DRASTICALLY ALTERED BECAUSE OF THE INFILTRATION OF THE LIQUID.

Supercontinuum Generation (SCG) with Near Zero ultra-Flat Dispersion PCF

Designing SCG requires information related to the nonlinearity and other related issues like dispersion profile of the fiber [Dudley et al, 2006; Agrawal et al, 2007;]. Nonlinear coefficient is one of the most important parameters for SCG and has been calculated using the following equation,

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}} \tag{5}$$

where n_2 is the non-linear refractive indices of the material (silica here) and A_{eff} is the effective area at that operating wavelength. The above data of a PCF so obtained are then used as input to the envelope based nonlinear Schrödinger equation (NLSE) which describes the pulse propagation through the PCF taking into account the contributions from the nonlinear effects, namely, self-phase modulation, Raman scattering, four-wave mixing. Eq. (6) represents the NLSE [Agrawal et al, 2007;] for slowly varying pulse envelope *A(z, T)* in the retarded time frame *T*

$$\frac{\partial A}{\partial T}+\frac{\alpha}{2}A-\sum_{n\geq 2}\frac{i^{n+1}}{n!}\beta n\frac{\partial^n A}{\partial T^n}=$$
$$i\gamma(1-f_R)([A]^2 A-\frac{i}{w_0}\frac{\partial}{\partial T}([A]^2 A)+i\gamma f_R(1+\frac{i}{w_0})$$
$$(A\int_0^\infty h_g(\tau)\left|A(z,T-\tau)\right|^2\partial\tau) \tag{6}$$

where α is the loss coefficient, β_n, the nth order dispersion, ω_0, the input pulse frequency, τ, the present time frame and f_R is the fractional contribution due to delayed Raman function $h_R(\tau)$ [Agrawal et al, 2007;]. NLSE is solved numerically by using the beam propagation code developed by COSTP11. In all the following cases we have considered the pulse to be *sech*^{2} type with different values of Full Width at Half Maximum (FWHM).

The previous section established that the value of first ZDW for three optimized PCFs are different to each other. This is significant because to achieve a broadband SCG, pump wavelength is an important issue. The different ZDWs signify we need different pump wavelengths. SCG for the optimized PCFs are studied for various pump wavelengths with subsequent parameters. Firstly, we considered the ultra-flat dispersion corresponding to Fig. 2 (the first optimized fiber) with Λ=0.94 μm and *d*=0.52 μm with liquid#1. The *ZDW* has been found out to be 1543 nm. We chose our pump to be around 1550 nm. The effective area variation with wavelength for all the optimized fibers are shown in Fig. 5 with the black, red and blue color variations represent optimized fibers with liquid#1, liquid#2 and liquid#3 respectively. The nonlinear parameter around the pumping wavelength has been found out to be 20.87 $w^{-1}.km^{-1}$. We have calculated the spectral width of the flat SC spectrum according to Begum et al, 2011. The numerical calculation shows a spectral width of FWHM of 370 nm around the pumping wavelength of 1550 nm that can be achieved with a fiber length of 0.75 meter as shown in Fig. 6. The corresponding values of the β_n (n=2 to 8) are mentioned in the second column of Table#1. The pump power was kept at 4.5kW with the FWHM of the pulse is of 1 ps. A possible source for such a pump can be the commercially available fiber laser emitting around 1550 nm of wavelength [Jackson et al, 2012;]. The calculated spectrum of the output power due to the propagation of the pulse is shown in Fig. 7.

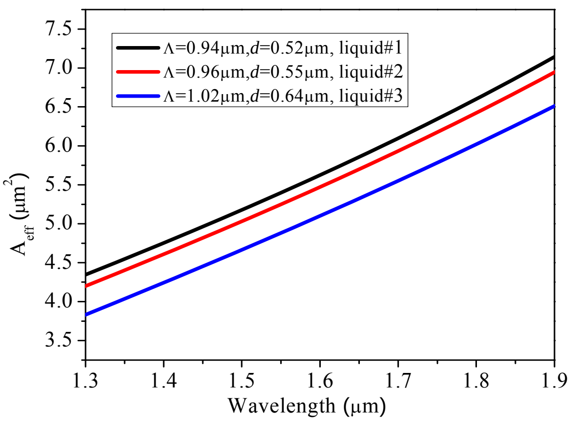

FIG. 5: EFFECTIVE AREA VARIATION FOR THE THREE OPTIMIZED ULTRA-FLAT DISPERSION PCF.

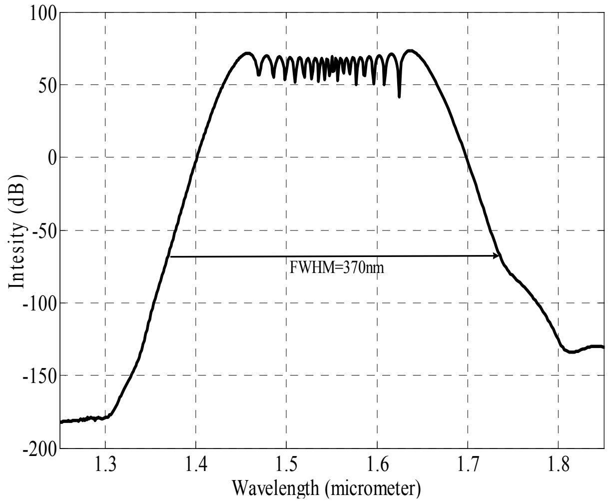

FIG. 6: OPTICAL SPECTRUM OF THE OPTIMIZED PCF WITH Λ=0.94MM, D=0.52MM WITH LIQUID#1 AFTER TRAVELLING A DISTANCE OF 0.75M.

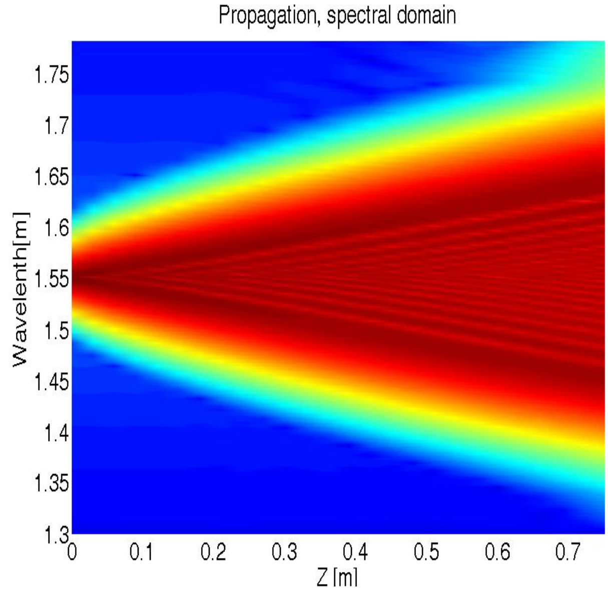

FIG. 7: SPECTRAL EVOLUTION AS A FUNCTION OF LENGTH OF THE FIBER FOR THE OPTIMIZED PCF WITH Λ=0.94MM, D=0.52MM WITH LIQUID#1.

Next, we considered the ultra-flat dispersion design shown in Fig. 2 (with red line) with Λ=0.96 μm and *d*=0.55 μm with liquid#2. The *ZDW* has been found out to be 1616 nm. The nonlinear parameter γ was found out to be 19.29 $w^{-1}.km^{-1}$ at the pump wavelength of 1620 nm. We obtained flat spectrum with FWHM of 400nm around the central pumping wavelength with a fiber length of 0.75 meters as shown in Fig. 8. The corresponding values of the β_n (n=2 to 8) are mentioned in the third column of Table#1. The calculated spectrum of the output power due to the propagation along the fiber of the pulse is shown in Fig. 9. The input power for the pulse is kept at 4.5 kW with FWHM of 1 *ps*.

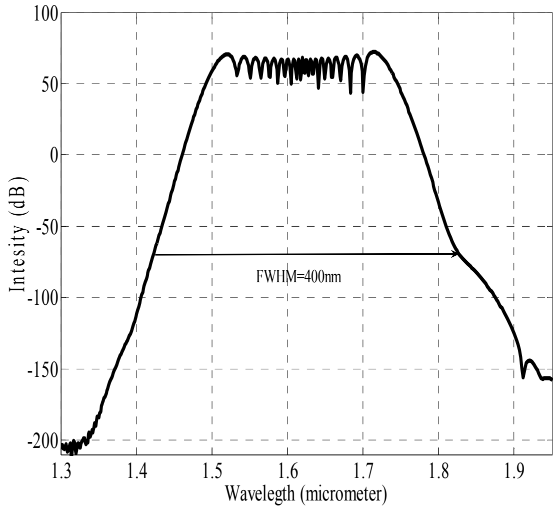

FIG. 8: OPTICAL SPECTRUM OF THE OPTIMIZED PCF WITH Λ=0.96MM, D=0.55MM WITH LIQUID#2 AFTER TRAVELLING A DISTANCE OF 0.75M.

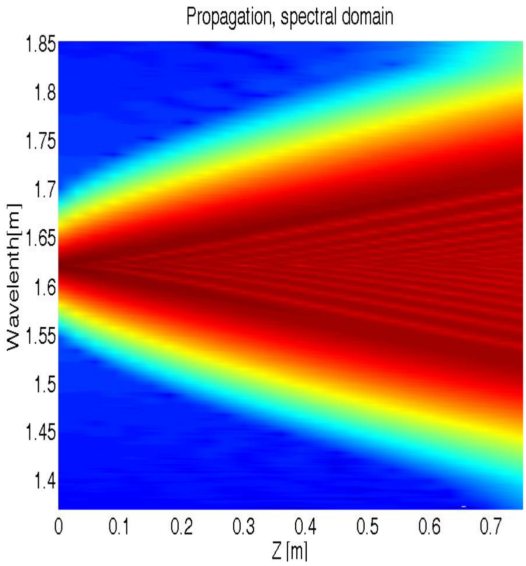

FIG. 9: SPECTRAL EVOLUTION AS A FUNCTION OF LENGTH OF THE FIBER FOR THE OPTIMIZED PCF WITH Λ=0.96MM, D=0.55MM WITH LIQUID#2.

We now consider the last of our ultra-flat dispersion PCFs shown in Fig. 2 (with red line) with Λ=1.02 μm and *d*=0.64 μm with liquid#3. The nonlinear parameter γ comes out to be 16.32 $w^{-1}.km^{-1}$ around the pump wavelength of 1790 nm, whereas the ZDW was found to be 1783 nm. With the above values we obtain a SC generation with flat spectrum with FWHM of 395 nm around the central wavelength with a fiber length of 0.60 meters as shown in Fig. 10. The corresponding values of the β_n (n=2 to 8) are mentioned in the fourth column of Table#1. The evolution of the spectrum along the fiber length of the pulse is shown in Fig. 11. The input power for the pulse is 4.5 kW with FWHM of 1.1 *ps* with the center wavelength of 1790 nm. In the last two cases of optimized fiber the possible pump source can be the commercially available IR laser sources with IOP Photonics.

One of the most salient features of the generated SC spectrum is that oscillatory structure can be observed playing along the spectral broadening covering the spectrum range. As can be seen clearly, the spectrum consists of many small peaks. These features show a typical pattern of self-phase modulation (SPM), which is assumed to be the dominant nonlinear effect responsible for the spectral broadening. The multipeak structure in the spectrum is a result of interference between the same optical frequencies in the pulse. We find that with the proposed PCF, the wavelength band of the generated SC is significantly wider due to the combination effect of SPM and near zero ultra-flattened dispersion. Additionally, the length of PCF is enormously small, thereby reducing the propagation losses.

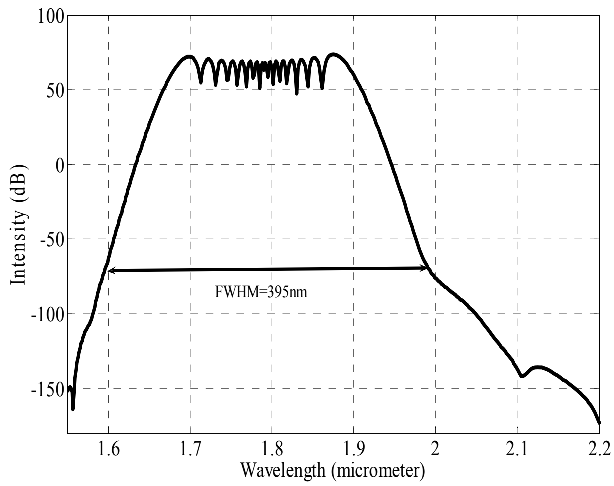

FIG. 10: OPTICAL SPECTRUM OF THE OPTIMIZED PCF WITH Λ=1.02MM, D=0.64MM WITH LIQUID#3 AFTER TRAVELLING A DISTANCE OF 0.60M.

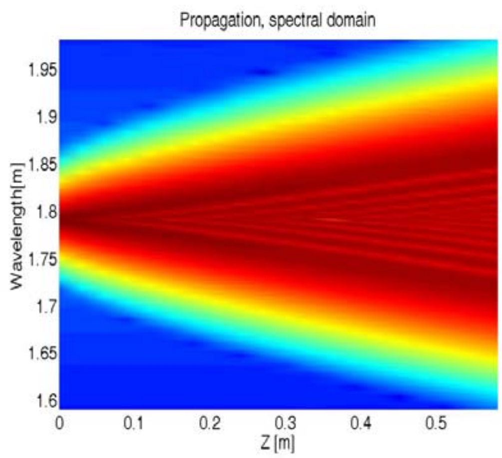

FIG. 11: SPECTRAL EVOLUTION AS A FUNCTION OF LENGTH OF THE FIBER FOR THE OPTIMIZED PCF WITH Λ=1.02MM, D=0.64MM WITH LIQUID#3.

TABLE 1: THE VALUES OF β_N USED FOR SIMULATION FOR THE THREE OPTIMIZED PCFS.

Beta values	Optimized fiber#1	Optimized fiber#2	Optimized fiber#3
β_2 (ps^2/km)	-0.4358	-0.1688	-0.55306
β_3 (ps^3/km)	-0.013481	0.01488	0.02838
β_4 (ps^4/km)	1.2440*10^{-4}	-2.8734*10^{-4}	2.7519*10^{-4}
β_5 (ps^5/km)	*4.89585*10^{-7}*	*3.75104*10^{-7}*	*5.31796*10^{-7}*
β_6 (ps^6/km)	*2.07899*10^{-8}*	-2.5916*10^{-8}	*6.06036*10^{-7}*
β_7 (ps^7/km)	*1.04043*10^{-10}*	1.80169*10^{-10}	*4.05304*10^{-10}*
β_8 (ps^8/km)	9.7393*10^{-14}	2.091*10^{-13}	1.018*10^{-13}

Conclusions

We have proposed a new design of achieving ultra-flat near zero dispersion PCF with all the air-holes are of equal dimension with one air-hole ring infiltrated with liquid. We performed a rigorous series study for optimization of the parameters that yielded an ultra-flat near zero-dispersion PCF with *D* as small as 0±0.41 *ps/nm/km* for a broad wavelength range of 452nm. Three such designs with practical index matching wavelength dependent liquid have been worked out. Numerical studies show that the proposed PCFs are suitable for flat top SCG in the wide broadband wavelength range of 4000 nm (approximately) with less than a meter long of the PCF. The proposed PCF structure can be very helpful in enormous engineering applications like dispersion compensation, Dense Wavelength Division Multiplexing (DWDM) system and ultra-short soliton pulse propagation etc.

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