# PROPERTIES OF PHOTONIC CRYSTAL FIBERS INFILTRATED WITH LIQUIDS

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**Abstract.** In this paper we present a numerical study of the dispersion characteristics of air-hole lattice photonic crystal fibers infiltrated with water-ethanol mixtures. We demonstrate the modeling results of dispersion characteristics for a fused silica glass fiber, in the temperature range from 10 °C to 60 °C associated with the concentration of ethanol of mixtures range from 30 % to 70 %. In our model, photonic crystal fibers are constructed as fused silica PCF with holes ordered in a hexagonal lattice, which consists of 7 rings of holes infiltrated with water-ethanol mixtures. For the optimized structure with flat dispersion characteristics, we consider numerically the influence of temperature and concentration of the ethanol solution on the dispersion of the fundamental mode for the case when the air holes are filled with water-ethanol mixtures.

**Keywords:** *Photonic crystal fiber, Dispersion, , Refractive index, Water-ethanol mixture, Fused silica.*

## I. INTRODUCTION

During the past years, photonic crystal fibers (PCFs) have attracted lots of research attention worldwide, because they have more degree of freedom in design and fabrication including guiding mechanism, type of lattice and lattice constant, shape and size of holes, free choice of glass type. PCFs have been intensively studied and found many applications such as fiber lasers, optical amplifiers, high-power transmission lines, supercontinuum generation devices, highly sensitive gas sensors and nonlinear devices [1-4].

PCFs allow us to coltrol the dispersion characteristics through the proper design of the internal structure, for instance, the changes in the shape and size of air-holes, or the replacement of air holes in the photonic cladding with other glasses and liquids. The dispersion properties have been studied both numerically and experimentally, including the zero-dispersion, the near-zero dispersion, the dispersion flattened, the ultra-flattened dispersion and the chromatic dispersion [5, 6]. One of the methods to engineer the dispersion properties of the PCFs is infiltrating the air-holes with some liquids. In Ref [7], J. Pniewski et al. reported a numerical study of the dispersion characteristic modification of nonlinear photonic crystal fibers based on the soft glass PBG-08, infiltrated with 17 liquids in air-holes in the cladding. The PCF with holes ordered in a hexagonal lattice had a lattice constant of approximately $\Lambda$ = 2.15 µm, a linear filling factor $d/\Lambda$ = 0.84 in the first ring, and a diameter of the core of 2.5 µm. The results showed that it is possible to control the zero-dispersion wavelength (ZDW) and the shape of the dispersion characteristic of a liquid-filled PCF by changes in the temperature. The ZDW is 1.355 µm for the PCF with air-holes, which is red shifted when the air-holes are filled with different liquids, such as 1.407 µm for water, 1.413 µm for methanol, 1.484 µm for toluene and 1.512 µm for nitrobenzene. This change allows matching the ZDW to available lasers used for soliton driven supercontinuum generation, when the pump wavelength is chosen near the ZDW on the anomalous dispersion region. In another study, the influence of temperature and concentration of the ethanol solution on the dispersion characteristics and the ZDW shift of fundamental mode are also investigated in Ref [8] on by L.Chu Van et al. It has been shown that water-ethanol mixture can be turned the dispersion properties of a regular lattice PCF made of fused silica glass. According to G. Stepniewski et al., experimental results have confirmed influence of temperature change in the range of 20 $^{o}$C - 420 $^{o}$C on dispersion characteristics of fused silica and heavy metal oxide glass nonlinear photonic crystal fibers. The correctness of the experimental results was confirmed with linear simulations performed for the fused silica glass fiber. The results shown that ZDW thermal shift is about +0.020 nm/$^{0}$C for fused silica fibers and +0.045 nm/$^{0}$C for the heavy metal oxide soft glass fiber [9]. As shown above, there are some questions above the dispersion characteristics of our PCF-NL33B2 made of fused silica, which is different to NAC21A in Ref. [8] and PCF NL33B1 in Ref. [9].

In this paper, we propose a PCF NL33B2 based on fused silica, infiltrated with water-ethanol mixtures. The fiber is designed and developed in the stack and draw process, which it is a real fiber. We calculate numerically the the dispersion of the fundamental mode with the help of MODE solutions by using the scanning electron microscope (SEM) images of the developed fiber, which is infiltrated with water-ethanol mixtures in the temperature range from 10°C to 60°C associated with the concentration of ethanol of mixtures range from 30% to 70%.

## II. DESIGN AND DEVELOPMENT OF THE PCF NL33B2

For simulations we consider a PCF fabricated and developed in the stack-and-draw process. The PCF is assembled fused silica capillaries into a preform “stack”, then obtained preform is inserted into a sleeve tube and drawn to fiber. The scanning electron microscopy (SEM) image of PCF is shown in Fig. 1. It includes 7 rings of air-holes

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ordered in a hexagonal lattice, which the core is solid. The PCF was designed for supercontinuum generation at 1300 nm. As a result, a supercontinuum was achieved in the bandwidth range of 700-3000 nm in a single-mode photonic crystal fiber [10].

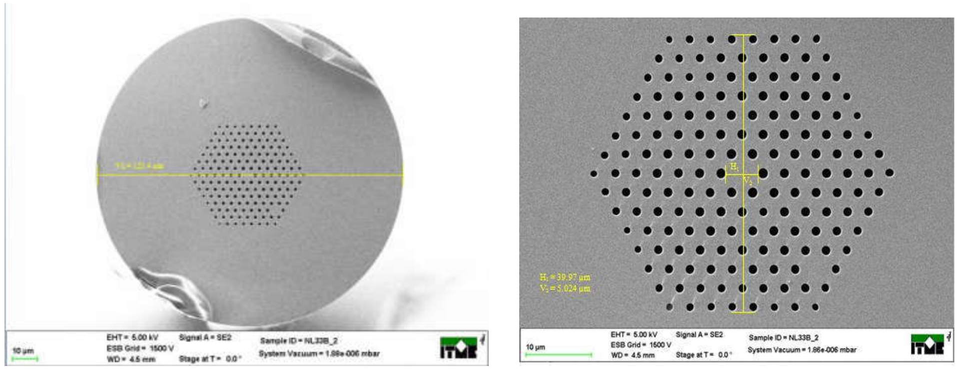

**Fig. 1.** *The scanning electron microscopy (SEM) image of PCF- fused silica fiber NL33B2. The diameter of the fiber is 123.4 µm. The diameter of core is 5.024 µm. The lattice constant of the fiber is while size of the air holes is 3.256 µm.*

The final developed fiber have a lattice constant around $\Lambda$ = 3.256 µm. The diameter of air holes is varying between 1.435 µm and 1.488 µm, as shown in Fig. 2, due to accuracy of fiber drawing process. The diameter of the core equals 5.024 µm. The first ring of holes in the cladding with a relative hole size is 0.54, which allows single mode performance of the fiber in the infrared range and reduces attenuation of the fundamental mode. In the numerical simulations, the refractive index distribution of the background glass was used by inputing the SEM image of the real fiber, which it includes all imperfections occurred during the development. The geometrical and optical parameters are given in Table 1.

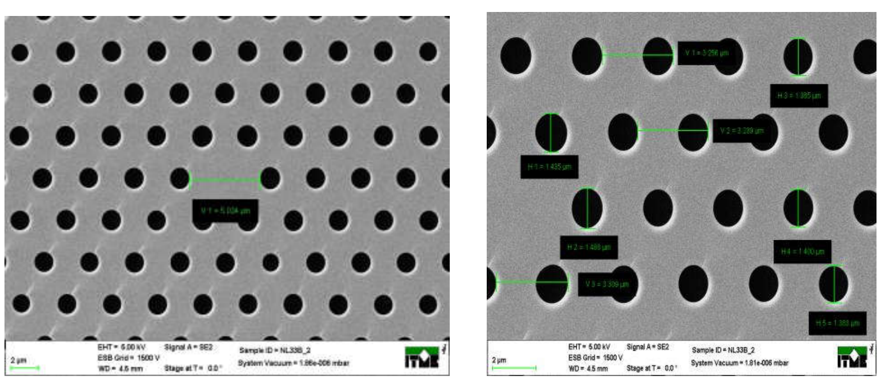

**Fig. 2.** *The SEM images of nonlinear photonic crystal fibers used in our work - fused silica fiber NL33B2, with $d_{core}$ = 5.024 µm, $\Lambda$ = 3.256 µm, d = 1.435 µm.*

The fused silica glass refractive index is described using the following Sellmeier relation [9]:

$$n(\lambda) = \sqrt{1 + \frac{B_1\lambda^2}{\lambda^2 - C_1} + \frac{B_2\lambda^2}{\lambda^2 - C_2} + \frac{B_3\lambda^2}{\lambda^2 - C_3}} \quad (1)$$

with coefficients: $B_1$ = 0.6694226, $B_2$ = 0.4345839, $B_3$ = 0.8716947, $C_1$ = 4.4801 x $10^{-3}$ $\mu m^2$, $C_2$ = 1.3285 x $10^{-2}$ $\mu m^2$, and $C_3$ = 95.341482 $\mu m^2$.

**Table 1.** *Geometrical and optical parameters of fused silica PCF NL33B2 [9].*

| Geometrical parameters | NL33B2 |
|---|---|
| Lattice constant - Λ [μm] | 3.256 |
| Core diameter - $d_{core}$ [μm] | 5.024 |
| Air hole diameter 1st ring - d [μm] | 1.488 |
| Relative air-hole size 1st ring - d/Λ | 0.45 |
| **Optical parameters [9]** | **Fused silica** |
| Refractive index - $n_D$ (for doublet sodium D-line at 589 nm) | 1.458 |
| Refractive index - $n_{1550}$ | 1.444 |
| Annealing point - $t_g$ [°C] | 1120 |
| Linear thermal expansion coefficient - $\alpha$ [$10^{-7}$/K] | 5.4 |

## III. NUMERICAL SIMULATIONS AND RESULTS

The PCF was investigated numerically based on SEM images, which the air-holes are infiltrated with water-ethanol mixtures. We considered numerically the influence of temperature and concentration of the ethanol solution on the dispersion of the fundamental mode when the air holes are filled with water-ethanol mixtures. The dispersion of water and ethanol are modelled using the following equation:

$$n(\lambda) = \sqrt{1 + \frac{B_1\lambda^2}{\lambda^2 - C_1} + \frac{B_2\lambda^2}{\lambda^2 - C_2}} \tag{2}$$

where $B_i$ and $C_i$ are the coefficients, as illustrated in Table 2 [8].

**Table 2**. *The coefficients of water and ethanol [8].*

| Sellmeier coefficients | Water | Ethanol |
|---|---|---|
| $B_1$ | 0.75831 | 0.83189 |
| $B_2$ | 0.08495 | 0.15582 |
| $C_1$ | 0.01007 | 0.00930 |
| $C_2$ | 8.91377 | 49.45200 |

Then, the refractive index of water-ethanol mixtures was calculated in the following equation:

$$n_{water-ethanol}(c) = c.n_e + (1-c).n_w \tag{3}$$

where $n_{water-ethanol}$ is the refractive index of water-ethanol mixture, c is the concentration of ethanol, $n_e$ is the refractive index of ethanol, $n_w$ is the refractive index of water.

We have calculated the dispersion characteristics as a function of the wavelength in the range of 0.5-1.6 μm for fundamentional mode of the developed fiber filled with water-ethanol mixtures. The temperature of liquids is changed in the range from 10 °C to 60 °C associated with the concentration of ethanol of mixtures range from 30 % to 70 %.

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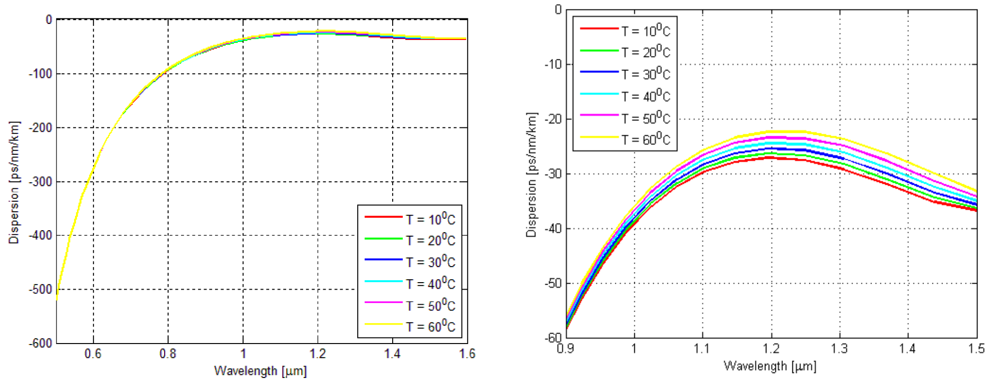


**Fig. 3.** *The dispersion characteristics of PCF of the fiber NL33B2 at concentration of ethanol 0.3 with various temperatures.*

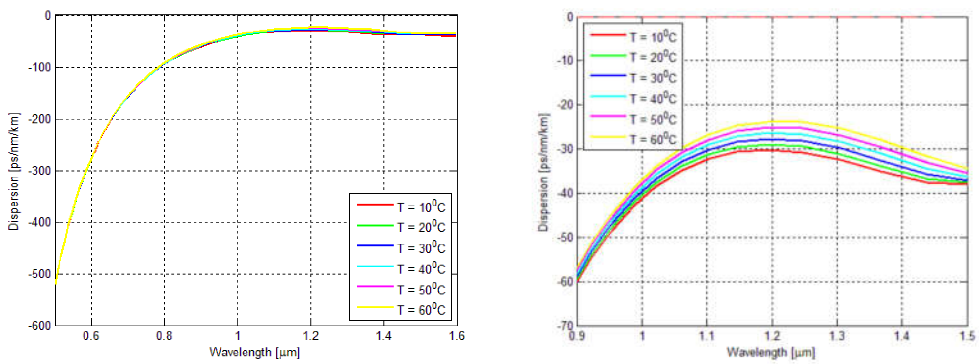


**Fig. 4.** *The dispersion characteristics of PCF of the fiber NL33B2 at concentration of ethanol 0.5 with various temperatures.*

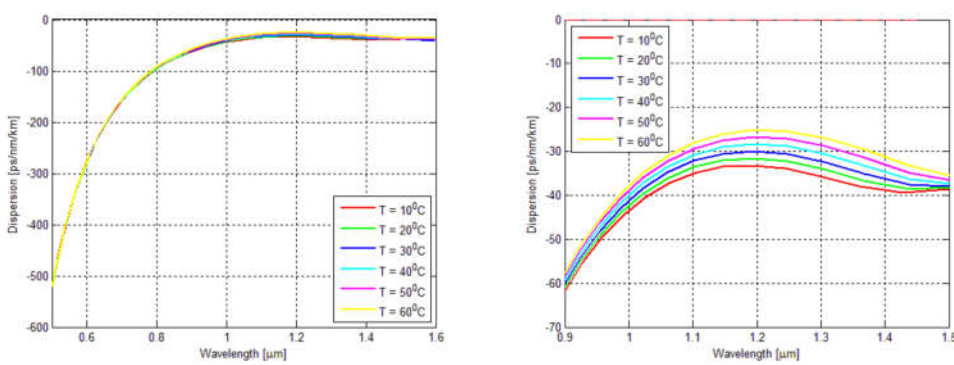


**Fig. 5.** *The dispersion characteristics of PCF of the fiber NL33B2 at concentration of ethanol 0.7 with various temperatures.*

The obtained results are shown in Fig. 3 – Fig. 5. Results of our simulations show that all fibers infiltrated with water-ethanol mixture have flat dispersion characteristics in the infrared range above 1000 nm. The dispersion characteristic is more flat at concentration of ethanol of 0.5, which the value of dispersion is reduced, less than 20 ps/nm/km. They are normal dispersion in all considered near infrared range. The local maximum is approximately of 1.3 µm, which is good to pump fiber for coherent supercontinuum. The dispersion characteristics of PCF can be tuned by changing the temperature and concentration of ethanol. When temperature increases dispersions characteristics become more flat, which is approached to the ZDW (close to zero). We consider a near-zero dispersion (NZD) band, which is an area that the dispersion ranges between -100 ps/nm·km and 100 ps/nm·km. This type of dispersion characteristics are very important for effective coherent supercontinuum generation. Our results show that the dispersion fits into NZD band in the full infrared wavelength range. Therefore, the fiber is a good candidate for generation of coherent supercontinuum.

## IV. CONCLUSION

In this paper, we presented a numerical study of the dispersion characteristic of PCF, which is filled by water-ethanol mixtures. PCF made of fused silica consisting of 7 rings of air-holes ordered in a hexagonal lattice with a diameter of the core equals 5.024 μm. We have shown that infiltration of air-holes of the fiber NL33B2 with water-ethanol mixtures significantly modify dispersion characteristic of PCF made of fused silica glass. We have shown that the dispersion is flat, which it is very important for efficient supercontinuum generation in fibres. The results showed that it is possible to control the shape of the dispersion characteristic of a liquid-filled PCF by changes in the temperature and concentration of ethanol.

## V. ACKNOWLEDGMENTS

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