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Measurement of temperature and concentration influence on the dispersion of fused silica glass photonic crystal fiber infiltrated with water–ethanol mixture

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A B S T R A C T

We present experimental and simulation results of the zero-dispersion shift in photonics crystal fibers infiltrated with water–ethanol mixture. The fiber based on the fused silica glass with a hexagonal lattice consists of seven rings of air-holes filled by liquid. We show that it is possible to shift the zero-dispersion wavelength by 35 ps/nm/km when changing the temperature by 60 °C, and by 42 ps/nm/km when changing the concentration of ethanol from 0 to 100%. The results also show that for the optical fiber filed with pure ethanol the flattened part of the dispersion shifts from anomalous to the normal regime at temperatures below −70 °C.

1. Introduction

Photonic crystal fibers (PCFs) have received much attention in the recent years because of their special properties such as: single mode operation over broadband [1], high numerical aperture [2], guidance in the air core [3], extremely small or extremely large mode areas [4], strong birefringence [5] and unusual chromatic dispersion [6]. Recently, PCFs have been applied in the fields of optical communication, fiber lasers and amplifiers [7], nonlinear optics [8], supercontinuum generation [9] and fiber sensors [10].

One of the most important properties of PCFs is related to the fact that it is easy to change their dispersion properties, i.e. to shift the zero-dispersion wavelength (ZDW) [11], achieve a large negative dispersion [12] and ultra-flat or normal dispersion in the required wavelength range [13,14]. The dispersion of PCFs is determined by the structure of the PCF, its lattice constant, and air hole diameter. For example, for a fiber with a triangle pattern of air holes, increasing the diameter of the air holes when the lattice is constant, the ZDW shifts to shorter wavelengths and the region of anomalous dispersion increases [15].

There is a wide range of materials used to fabricate PCFs, including pure silica, doped silica and other glasses [16]. The use of different materials opens up a new degree of freedom for the fiber design. In particular, the use of different materials makes it possible to move the ZDW and modify the shape of the dispersion. The dispersion of the PCF can be further modified when the air holes are infiltrated with various liquids such as polymers [17], water [18], ethanol [19] and liquid crystals [20]. By choosing the liquids, one can shift the ZDW, as well as modify the curvature of fiber dispersion characteristics [21,22]. Depending on the refractive index of the liquid, the guiding effect of the fiber can possibly be changed from guiding based on the modified total internal reflection, to guiding based on the photonic band gap effect, where the core has a lower refractive index than the effective index of the cladding. Also selective filling of PCFs, where only some of the holes are infiltrated, has experienced a considerable interest [23], because this can be used to tailor the optical characteristics of the PCF e.g. to obtain the near-zero ultra-flat dispersion, or to fabricate fibers with low insertion loss. Filling fibers with liquids, in particular ethanol, is also used to construct optical temperature sensors [24–26], control

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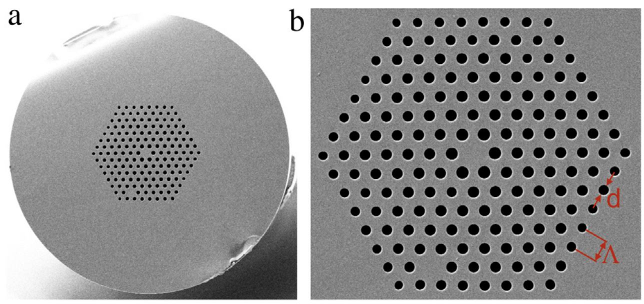

Fig. 1. The scanning electron microscopy images of fabricated PCFs.

the birefringence of the fiber [27] and to strengthen the nonlinear effects [19].

The optical characteristics of the fiber, especially infiltrated with liquid crystals, can also be changed by varying the temperature, since the ordinary and extraordinary refractive indices of liquid crystals highly depend on temperature [28]. The liquid can be infiltrated into the PCF using various techniques. One of the possibilities is to infiltrate the holes of the PCFs using capillary forces [29]. A disadvantage of using capillary forces for the infiltration is that the length of the infiltrated region will only be of the order of a few centimeters, while longer infiltration lengths can be achieved using pressure infiltration [29]. Thus, other techniques have been developed to selectively fill PCF by liquids [23,30]. In our experiments both capillary forces and pressure infiltration are used.

In this paper, we focus on the fused silica PCF with a regular lattice infiltrated by water-ethanol mixture and we investigate the influence of temperature and ethanol in water concentration on the dispersion characteristics and the ZDW shift. Infiltration of the PCF with ethanol–water mixtures is very interesting for several reasons. Due to its small viscosity the mixture can penetrate very small holes. Moreover it is non-toxic. Because the surface of the holes is very small, the evaporation is very limited. Thus, ethanol-water mixtures can be efficiently used for PCF dispersion tuning with temperature and concertation. We present both the results of computer simulations and their experimental verification in laboratory conditions. The simulations are based on the scanning electron microscope (SEM) images of the fiber. In the simulations we include the change in the temperature of the water-ethanol mixture from 10 °C to the boiling point and ethanol concentration in water from 0% to 100%. We also present the results of simulations for pure ethanol at temperatures below zero. We experimentally confirm the simulation results for several concentrations and temperatures. Such a comparison between the experimental and simulation results, for filling fiber by water-ethanol mixture and its influence on dispersion properties has not been presented so far.

2. Fiber fabrication

The fiber was made of fused silica glass and fabricated using the stack and draw method. It consists of seven rings of air holes ordered in a hexagonal lattice with a solid core. The lattice of the fabricated fiber (Fig. 1) is approximately $\Lambda = 3.38$ μm, the filling factor $d/\Lambda = 0.55$ in the first ring and the core diameter equals 4.73 μm. For the remaining outer rings, the diameter of the air holes varies between 1.25 μm and 1.77 μm with the filling factor ranging between 0.37 and 0.52.

3. Nummerical modeling

The developed fiber was numerically investigated based on the SEM images. The fused silica glass refractive index is described using the Sellmeier relation [31]. In the simulations, a constant value $k = 1\times10^{-6}$ of losses (extinction) was assumed.

We also assumed that the air-holes are infiltrated with water-ethanol mixtures. In simulations, we considered the influence of temperature and concentration of the ethanol in water on the dispersion of the fundamental mode. The fundamental mode and the dispersion properties of the PCFs were calculated by using a commercial-grade simulator eigenmode solver [32]. We have verified the correctness of the calculated effective refractive index as a resolution of the mesh used.

The refractive index of the water-ethanol mixture is a function of wavelength λ, temperature t and volume fraction of ethanol v (also referred as the ethanol concentration in water or water-ethanol mixture concentration). It is given by the following formula [33]:

$$n_{ew}(\lambda, t, c) = v\, n_e(\lambda, t) + (1 - v)\, n_w(\lambda, t) \tag{1}$$

where n_{ew}, n_e and n_w denote refraction indices of the water-ethanol mixture, ethanol and water, respectively.

In the case of water, Cauchy formula with temperature dependent coefficients was used [34]:

$$n_w(\lambda, t) = A(t) + \frac{B(t)}{\lambda^2} + \frac{C(t)}{\lambda^4} + \frac{D(t)}{\lambda^6} \tag{2}$$

where λ is the wavelength in nanometers, t is the temperature in Celsius and $A(t)$, $B(t)$, $C(t)$, $D(t)$ are Cauchy coefficients, which are the functions of temperature, according to the equations [35]:

$$A(t) = 1.3208 - 1.2325\times10^{-5}t - 1.8674\times10^{-6}t^2 + 5.0233\times10^{-9}t^3$$

$$B(t) = 5208.2413 - 0.5179t - 2.284\times10^{-2}t^2 + 6.9608\times10^{-5}t^3$$

$$C(t) = -2.5551\times10^{8} - 18341.336t - 917.2319t^2 + 2.7729t^3$$

$$D(t) = 9.3495 + 1.7855\times10^{-3}t + 3.6733\times10^{-5}t^2 - 1.2932\times10^{-7}t^3. \tag{3}$$

In the case of ethanol, the dependence of the refractive index n_e on the temperature t is brought by the formula [35]:

$$n_e(\lambda, t) = \sqrt{1 + \frac{B_1\lambda^2}{\lambda^2 - C_1} + \frac{B_2\lambda^2}{\lambda^2 - C_2}} - \alpha_e\left(t - T_0\right) \tag{4}$$

where the dependency of the refraction index on the wavelength is given by the Sellmeier formula ($B_1 = 0.83189, B_2 = -0.15582, C_1 = 0.0093$ μm^2, $C_2 = 49.452$ μm^2 [31]), and the dependency of the refraction index on the temperature is a correction proportional to the material temperature coefficient of the refractive index $\alpha_e = 3.94\times10^{-4}$. The reference temperature T_0 is 20 °C. Figs. 2 and 3 show the examples of how the refractive index of the fundamental mode LP01 for the fiber filled with the water-ethanol mixture depends on the various wavelengths, temperatures and volume fractions. Fig. 4 shows an example of the fundamental mode field distribution for 1 μm wavelength and the effective mode area for three fibers: (a) with air holes, (b) infiltrated with water, and (c) infiltrated with ethanol. The results show that the effective mode area is smallest for the dry fiber and biggest for the fiber filled with ethanol. This is related to the fact that the refractive index contrast between the glass material in the core and the material in the holes is smallest for ethanol and biggest for the dry fiber. An increase of the effective mode area in fibers filled with liquids results in a decrease of the light energy propagating in the core, which may result in lower SC generation efficiency.

Simulations do not take into account of the thermal expansion and changes in the refractive index with temperature of the glass due to their negligible variation in the considered temperature range (0.55×10^{-6} °C^{-1}). Also, losses in water-ethanol mixture was not included because the majority of energy propagates in glass, whose losses were taken into account, while the losses in liquids filling small holes are small. In the simulations we calculated the dispersion of the fundamental mode for the fiber filled by a water–ethanol mixture. Calculations were performed for the wavelength in the range from 0.5 to 1.7 μm, for ethanol concentration in water from 0% to 100% and for the temperature