Temperature Dependence of Liquid Filled Photonic Crystal Fibers

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Abstract— The effects of temperature on dispersion, effective area and nonlinearity of an index-guiding hexagon photonic crystal fiber filled by ethanol are described by using the vectorial beam propagation method, and a nearly zero ultra flattened dispersion fiber is optimized design with the dispersion coefficients of $0 \pm 0.5\,\mathrm{ps/(nm \cdot km)}$ at the wavelength of $1.46\,\mu\mathrm{m}$ to $1.65\,\mu\mathrm{m}$. The results indicate that increasing temperature could lead to increase dispersion and nonlinearity, but decrease the dispersion slope so as to flatten the dispersion. The result provides theoretical base for designing continuously tailoring dispersion optical communication components or optical sensing devices.

1. INTRODUCTION

Photonic crystal fiber (PCF) [1], also called holey fiber (HF), has air holes arranging according to a certain rule in the cross section, and constant along the length of the fiber. Compared with the conventional fiber, photonic crystal fiber has many unique characteristics due to flexible design, for example, endless single mode transmission [2], Sensitive structure capable of dispersion characteristics [3, 4], Nonlinear controllability [5] etc..

Dispersion is one of the key factors affecting optical fiber transmission and transmission distance, near zero dispersion fiber and broadband ultra flattened dispersion characteristic have potential applications. The structural parameters and optimization of optical fiber can be tailored to achieve nearly zero ultra flattened dispersion, such as the ultra flattened dispersion of $0 \pm 0.8\,\mathrm{ps/(nm \cdot km)}$ at the wavelength of $1.515\,\mu\mathrm{m}$ to $1.622\,\mu\mathrm{m}$ designed by Chen Ming [6] et al., and $0 \pm 0.65\,\mathrm{ps/(nm \cdot km)}$ at the wavelength of $1.36\,\mu\mathrm{m}$ to $1.62\,\mu\mathrm{m}$ designed by Feroza Begum [7] et al.. In addition, liquid such as water, ethanol, polymer etc. is filled in the air holes to tailor its characteristics. Krishna Mohan Gundu [8] ever reported the realization of the broadband nearly zero flattened dispersion fiber by filling liquid in PCF, low dispersion is obtained within $0 \pm 0.5\,\mathrm{ps/(nm \cdot km)}$ in the 400 nm bandwidth, but for nonlinear and temperature dependence are not in-depth analysis.

In this letter, we simulate the transmission characteristics of liquid filled photonic crystal fiber by using the vectorial beam propagation method (VBPM) [9], and analyze the influence of temperature on the dispersion, effective area and nonlinearity. A nearly zero ultra flattened dispersion fiber is optimized design, which dispersion coefficients ranges from $0 \pm 0.5\,\mathrm{ps/(nm \cdot km)}$ at the wavelength of $1.46\,\mu\mathrm{m}$ to $1.65\,\mu\mathrm{m}$. The result provides theoretical base for designing continuously tailoring dispersion optical communication components or optical sensing devices.

2. THEORY

Cross index profile of an index-guiding hexagon photonic crystal is shown in Fig. 1, d_1 to d_4 present air hole diameters of one to four layers from the core outward, Λ is hole pitch. Ethanol is filled into the air holes of all, because of the refractive index of ethanol is smaller than the quartz's, so optical fiber is based on total internal reflection. The total dispersion of photonic crystal fiber can be described as follow [10]

$$D(\lambda) = -\frac{\lambda}{c}\frac{d^2 n_{eff}}{d\lambda^2} + D_M(\lambda) \tag{1}$$

where λ is the vacuum wavelength, c is the speed of light in vacuum, n_{eff} is the effective refractive index, and $D_M(\lambda)$ as the material dispersion. The nonlinear coefficient of photonic crystal fiber is described as

$$\gamma = \frac{n_2 \omega_0}{cA_{eff}} = \frac{2\pi n_2}{\lambda A_{eff}} \tag{2}$$

here $n_2 = 2.76 \times 10^{-20}\,\mathrm{m^2/W}$ for nonlinear refraction rate of quartz, and ω_0 is the angular frequency. The fiber effective area of fundamental mode is defined as

$$A_{eff} = \left(\iint_s |E_t|^2\, dxdy\right)^2 \Big/ \left(\iint_s |E_t|^4\, dxdy\right) \tag{3}$$

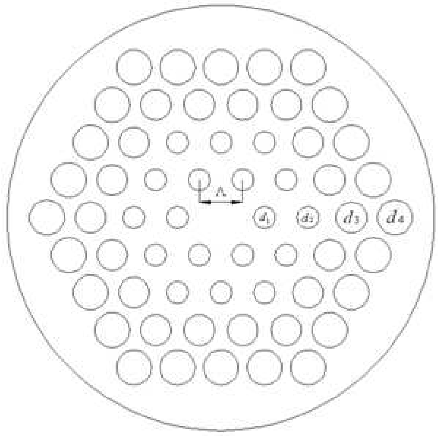

Figure 1: Cross profile of the ultra-flattened dispersion photonic crystal fiber.

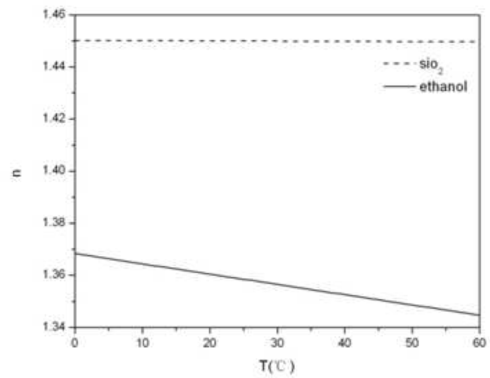

Figure 2: The refractive index of SiO_2 and ethanol at different temperatures.

where E_t is the horizontal electric field vector, s is the cross-section of the photonic crystal fiber. Material temperature coefficient of refractive index is defined as [11]:

$$\alpha = (n_0 - n)/(T - T_0) \tag{4}$$

where T is the operating temperature, T_0 is 20°C, n and n_0 are the refractive index at temperature of T and T_0.

Ethanol is filled in the air holes, it is high temperature coefficient relevant with refractive index, the temperature coefficient of ethanol is $\alpha_{ethanol} = 3.94 \times 10^{-4}$/K, and the temperature coefficient of quartz is $\alpha_{sio_2} = 8.6 \times 10^{-6}$/K, the temperature coefficient of quartz is two orders of magnitude lower than that of ethanol.

3. CALCULATED RESULTS AND ANALYSIS

Figure 2 is the refractive index curve of quartz and ethanol at different temperatures, compared with ethanol, the refractive index change of quartz can be ignored. When the temperature is 20°C, the parameters $d_1 = 0.53\Lambda$, $d_2 = 0.52\Lambda$, $d_3 = 0.7\Lambda$, $d_4 = 0.8\Lambda$, $\Lambda = 2.75\,\mu$m, photonic crystal fiber dispersion curve is shown in Fig. 3, at the wavelength range of 1.46 μm to 1.65 μm the absolute value of dispersion is less than 0.5 ps/(nm · km). Choosing this kind of fiber parameters can realize broadband near zero low dispersion transmission. On the basis of this, filling pore air with ethanol, the temperature effect on the dispersion is shown in Fig. 4, when temperature is 0°C, 20°C, 40°C, and 60°C, there has been a significant change in dispersion. In the short wavelength range, the higher the temperature, the greater the value of dispersion, and the smaller dispersion slope. At the 1.55 μm wavelength, the dispersion of 0°C is 1.9036 ps/(nm · km) lower than 20°C, the dispersion

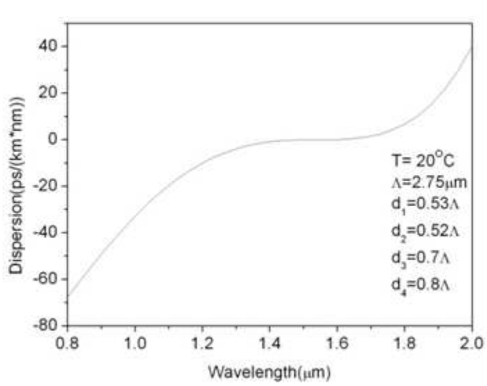

Figure 3: Dispersion curves of designed PCF.

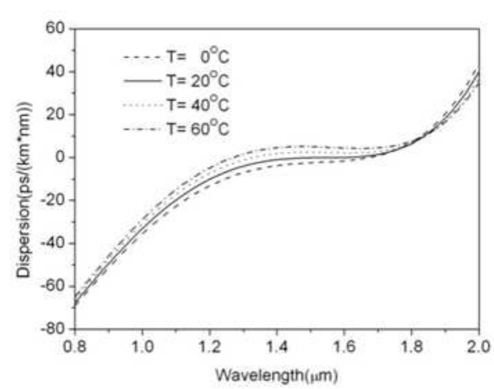

Figure 4: Dispersion curves at different temperatures.

of 20°C is 2.2895 ps/(nm · km) lower than 40°C, and the dispersion of 40°C is 2.4943 ps/(nm · km) lower than 60°C.

Figures 5 and 6 are the curves of the fiber mode field area and the effective nonlinear coefficient varies with temperature. The effective area increases with long wavelength, because the long wave optical field has better penetration ability into the pack layer hole than the short wave; at short wavelengths, the light energy is concentrated in the core, so the effective area is smaller. With the increase of temperature, ethanol refractive index is smaller, the effective refractive index of cladding reduces, so as to enhance the ability of local light, and thus area reduce effectively. At the 1.55 μm wavelength, the effective area of 0°C is 1.6868 μm^2 larger than 20°C, the effective area of 20°C is 1.1734 μm^2 larger than 40°C, and the effective area of 40°C is 0.8007 μm^2 larger than 60°C. With the increase of temperature and the temperature interval of the same, the difference of effective area is more and more small. This is because, with the increase of temperature, the refractive index of ethanol decreases, the cladding mode's effective refractive index decreases, the local capacity to light becomes strong, leading to the effective area is reduced, and the light field is more concentrated to the core and gradually away from the cladding layer, so the influence of liquid refractive index of the outer air hole on it is more and more small. In contrast, the nonlinear coefficient decreases with the increasing of wavelength, increases with the increasing of temperature, at the 1.55 μm wavelength, the nonlinear coefficient of −20°C is 0.2840 W^{-1} km $^{-1}$ smaller than 0°C, the nonlinear coefficient of 0°C is 0.2339 W^{-1} km^{-1} smaller than 20°C, the nonlinear coefficient of 20°C is 0.1899 W^{-1} km^{-1} smaller than 40°C, the nonlinear coefficient of 40°C is 0.1453 W^{-1} km^{-1} smaller than 60°C.

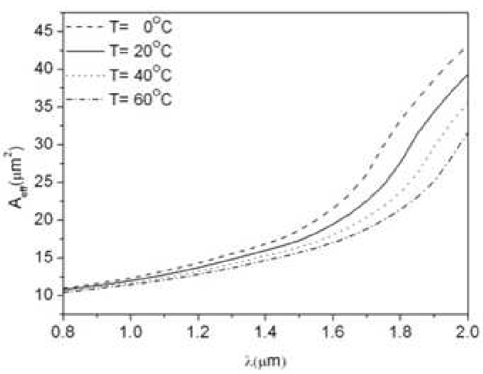

Figure 5: Effective area A_{eff} curves at different temperatures.

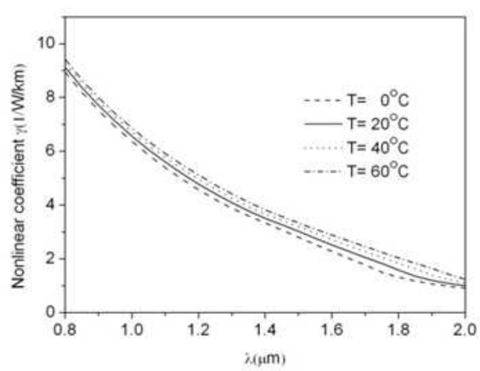

Figure 6: The nonlinearity curves at different temperatures.

4. CONCLUSIONS

The vectorial beam propagation method (VBPM) is used to simulate and analysis the characteristics of photonic crystal fiber. A nearly zero ultra flattened dispersion fiber with an index-guiding hexagon is optimized design, in the wavelength range of 1.46 μm to 1.65 μm, the dispersion coefficients ranges from 0 ± 0.5 ps/(nm · km), we fill the air hole with ethanol and study the temperature dependence of PCF. The results indicate that increasing temperature could lead to increase dispersion and nonlinearity, but decrease the dispersion slope so as to flatten the dispersion. These provide a theoretical reference for the use of optical fiber fabrication of continuous adjustable devices in optical communication and optical sensing transmission performance.

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