Highly Birefringence Elliptical Hole Photonic Crystal Fiber for Pressure Sensing

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***Abstract*- This paper focuses on the applications of photonic crystal fibers (PCFs) for pressure sensing. We have analyzed and designed the properties of a high birefringence PCF for sensing pressure which composed of a solid silica core and a cladding with elliptical air holes. The high birefringence is introduced on the combined effect of elliptical air holes which are three different sizes in cladding. Our numerical result shows that birefringence can reach as high as 0.011 at 1.55µm wavelength with a properly designed cladding structure. We also analyze the effect of other structural parameters on birefringence**.

Keywords*- *Photonic crystal fiber, Birefringence, elliptical airholes

I. INTRODUCTION

Photonic crystal fibers (PCFs) have attracted a lot of research attention due to many possibilities and promising applications in communication and sensing [1]. The birefringence of index guiding PCFs has a magnitude of the order of 10^{-3}, which is 1 order of magnitude higher than the conventional fiber (the order of 10^{-4}) [2]. Using PCFs, highly birefringence fiber can be easily realized, because the core-cladding index contrast is higher than that of conventional fiber and the fabrication process permits the formation of the required asymmetric microstructure near the fiber core. Generally, two different kinds of PCFs exist, classified by their light-guiding mechanism. The first type guides by a modified form of total internal reflection (M-TIR) and fibers of this type are also known as index-guiding PCFs and second type provides guidance by the photonic bandgap (PBG) effect which provides novel features such as light confinement to a low-index core [4-6]. Due to high index difference index guiding photonic crystal fiber opens a wide range of application properties PCF have achieved excellent properties in birefringence, dispersion, single polarization single mode nonlinearity and effective mode area over the past several years[6-8].PCFs have shown some advantages for applications in optical fiber sensors, such as temperature insensitivity for strain sensing, high sensitivity for pressure sensing and so on [7-11]. Compared with conventional single mode fiber (SMF), MSF is superior in acting as a stress-optic component.

By utilizing the physical property of the air-glass structure, the four-hole fiber can be used as a hydrostatic pressure sensor element offering high sensitivity. In this paper, we have proposed a highly birefringence six elliptical hole fiber with a birefringence up to 0.012. In this design, six elliptical air holes are employed which ensures high birefringence of the six-hole elliptical fiber (SHEF).

II. THEORY

Birefringence is the result from residual strain following the drawing process, or slight accidental distortions in geometry, which can cause significant birefringence because of the large glass–air index difference. If, however, the core is deliberately distorted so as to become twofold symmetric, extremely high values of birefringence can be achieved. For example, by introducing capillaries with different wall thicknesses above and below a solid glass core value of birefringence some 10 times larger than from conventional fibers can be obtained [6]. The phase modal birefringence of the optical fiber is defined as,

$$B= n^{y}_{eff} - n^{x}_{eff} \qquad (1)$$

where n^{x}_{eff} and n^{y}_{eff} are the effective indices of the *x*-polarized mode and *y*-polarized mode of the optical fiber, respectively.
When the SHEF is subjected to an air/hydrostatic pressure, the stress induced by the pressure will result in refractive index change due to the photo-elastic effect. The refractive index of the pure silica subjected to the pressure is given by [7]

$$n_x=n_0 - C_1\sigma_x - C_2(\sigma_y+ \sigma_z) \qquad (2)$$

$$n_y=n_0 - C_1\sigma_y - C_2(\sigma_x+ \sigma_z) \qquad (3)$$

Where σ_x , σ_y , σ_z are the are the stress components, $C_1= 6.5*10^{-13}$ m^2/N and $C_2=4.2*10^{-13}$ m^2/N are the stress-optic co-efficient of pure silica.
The pressure-induced index change is

$$\delta n_x=n_x - n_0= - C_1\sigma_x - C_2(\sigma_y+ \sigma_z) \qquad (4)$$

$$\delta n_y=n_y - n_0= - C_1\sigma_y - C_2(\sigma_x+ \sigma_z) \qquad (5)$$

and the pressure-induced birefringence is,

$$\delta B= n_y - n_x=(C_2 - C_1)(\sigma_x - \sigma_y) \qquad (6)$$

An important parameter of the PCF for pressure sensing is the polarmetric pressure sensitivity, which is defined as[8],

$$K_p=(2\pi/\lambda)(dB/dP) \quad (7)$$

where λ, dB, dP are the operation wavelength, pressure change and pressure-induced birefringence, respectively. We also use the FEM to calculate the stress distribution.

The boundary condition for external perimeter of the fiber is set to perfect magnetic conductor. The perfect magnetic conductor boundary condition

$$\mathbf{n} \times \mathbf{H} = \mathbf{0}$$

sets the magnetic field to zero at a boundary.

The other perimeter is set to continuity inside the PCF. The continuity boundary condition

$$\mathbf{n} \times (\mathbf{H}_1 - \mathbf{H}_2) = \mathbf{0}$$
$$\mathbf{n} \times (\mathbf{E}_1 - \mathbf{E}_2) = \mathbf{0}$$

is the natural boundary condition ensuring continuity of the tangential components of the electric and magnetic fields.

There are seven sub-domains for this design. One for the sillica and other six for the six air holes. The refractive index for sillica sub-domain is set to 1.45 and the refractive index of airholes sub-domain is set to 1.

III. DESIGN TOOL

The COMSOL Multiphysics version 3.2a is used to design the SHEF. MATLAB 7.0 is used to plot the graph.

IV. DESIGN AND STRRUCRURAL PARAMETER

Cross- section of the designed fiber is depicted in Fig. 1. A pair of large elliptical air holes, a pair of mid size elliptical air holes and a pair of small elliptical air holes is employed for this fiber. The fiber radius (R) is also an important structural parameter. The edge to edge distance between two small elliptical air holes (H) ensures the light confinement. The center to center distance between mid sized elliptical air holes (L) has impact on light confinement and elliptical ratio (ER) also plays an important role for gaining high birefringence.

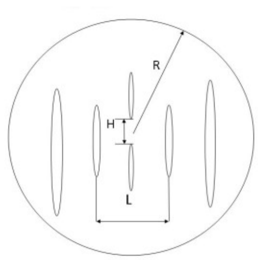

Fig 1: Cross-section of the SHEF

V. RESULTS AND DISCUSSION

Following the analysis and design in the preceding sections, we have simulated the properties of the PCF using COMSOL Multiphysics software. We have an extended search for acquiring high birefringence by varying different structural parameter. Fig. 2 shows the plots of birefringence vs edge to edge hole distance. At first we set the *L* at 6μm and change the *H* . we find high birefringence at 1μm at 1550nm wavelength. The plot of the simulation is given in Fig 2.

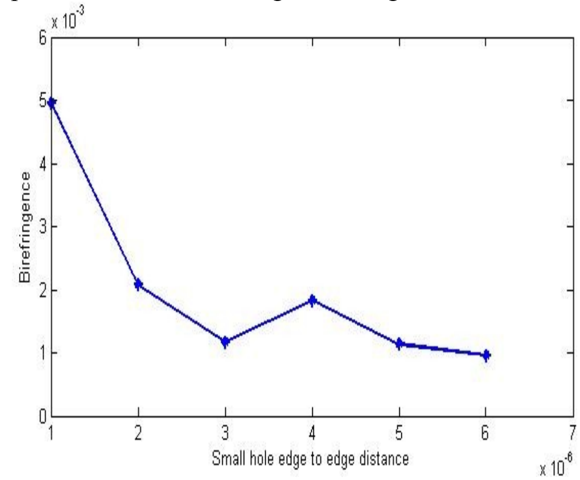

Fig 2: Plot of Birefringence and Edge to edge distance of small hole

The plot shows high birefringence at the 1μm. It has a slight rise of birefringence at 4 μm but still lower than the birefringence at 1 μm. The plot is almost linear. The birefringence decreases as the edge to edge hole distance reduced.

Now we would like to explore a distinctive parameter for gaining high birefringence. Maintaining *H* constant we now change the distance *L* for finding high birefringence. For center to center distance of mid size hole L we find maximum birefringence at 4 μm at 1550nm wavelength. The plot of the simulation is given in Fig 3.

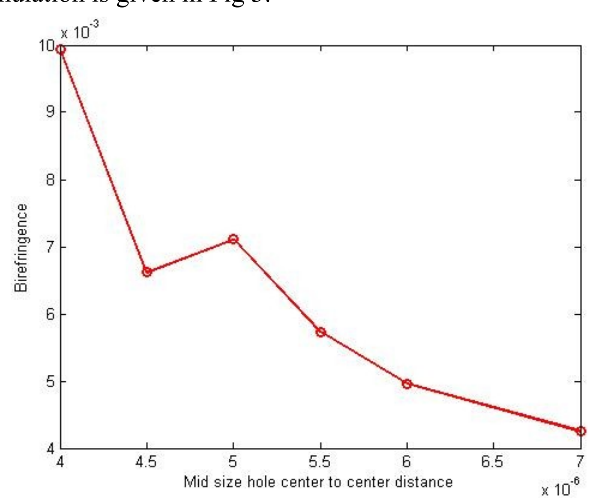

Fig 3: Plot of Birefringence and center to center distance of mid sized hole.

The above plot shows a slight rise in birefringence at 5μm but still lower than birefringence at 4μm . So birefringence is highest at when center to center distance of mid size-hole is 4μm and Edge to edge distance of small hole 1μm. For both situation fiber radius is 9μm and the wavelength is at 1550nm.

Fiber radius (R) also influences birefringence. Birefringence also has almost linear relationship with fiber radius. The plot birefiengence vs. fiber core radius in Fig. 4. Birefringence has a fall at 15μm fiber radius. It also maintains a almost linear relationship with the radius.

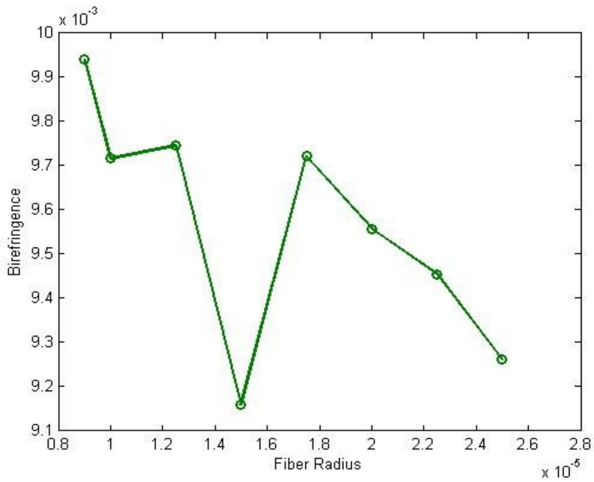

Fig 4: Plot of birefringence and fiber radius

Pressure is sensed by change of the wavelength. If birefringence is changed with the change of wavelength then it can be considered as sensor. This figure also indicates that by decreasing elliptical ratio (ER) birefringence is higher. In fact at ER=5 birefringence is above 0.01. Decreasing ER increase birefringence is also found in [12].

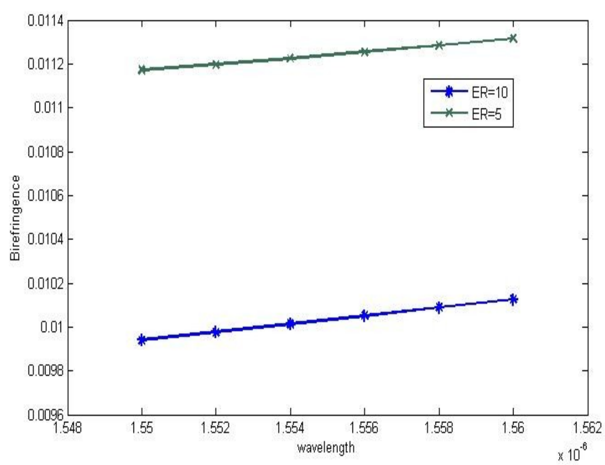

Fig 5: Plot of birefringence and wavelength

High birefringence is attained by the arrangement of the air holes. Since air holes long axis is in y-direction, so y-axis has the larger effective index.

VI. Conclusion

We have studied the high birefringence PCF with six elliptical air holes. The high birefringence is introduced by the combined effect of elliptical air-hole and different sizes of air holes in the cladding. Our numerical results indicate that the birefringence can be obtained as high as 0.01 at 1.55μm wavelength with a properly designed cladding structure. We also analyze effect of other structural parameter. This PCF is relatively easy to design and fabrication is less complex though maintaining a high sensitivity.

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