

Polarization Properties of Photonic Crystal Fibers Considering Thermal and External Stress Effects

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Abstract— Analysis of the effects of thermal and external stress on the properties of solid core photonic crystal fibers has been carried out in this work by using the finite element method. The external stress acting on the fiber induces a specific stress distribution on the fiber's cross section making the isotropic fiber material birefringent. The effective index of the fiber under stress decreases almost linearly with a significant increase in the birefringence over a wide operating wavelength (0.7 μ m–2.0 μ m). With the increase of the wavelength at all considered external stress (up to 4GPa), the polarization mode dispersion decreases almost linearly. The study shows that the dispersion in the photonic crystal fiber exhibits anomalous values, revealing that at specific value of external stress, the fiber exhibits specific dispersion values. Thus, the photonic crystal fiber has got tremendous potential to be used as dispersion compensating device in the field of optical communications and other fields of applications.

Keywords— Photonic crystal fiber, finite element method, elasto-optic effect, birefringence, polarization mode dispersion.

I. INTRODUCTION

In the recent years, there has been a significant interest among the fiber-optic researchers on photonic crystal fibers (PCFs), which are also called microstructured optical fibers [1]-[15]. These PCFs are usually made of a single material, e.g., pure silica (SiO₂) or polymer [2]-[5] formed by a central solid defect region surrounded by cladding consisting of a two dimensionally periodic array of multiple air holes in a regular triangular or rectangular lattice, where the air holes run along the length of the fiber. At present, there are two types of PCFs, holey fibers and bandgap fibers [2]-[5]. The core in PCF is a deliberate defect region, where there is a missing air hole in the center in case of holey fibers and a central air hole in case of bandgap fibers. Light confinement is explained by two different mechanisms: the index guiding effect; and the photonic band-gap effect. PCFs offer a number of unique and useful properties [1]-[15], such as a wide single-mode wavelength range, anomalous group velocity dispersion (GVD) which are not achievable in traditional silica glass fibers. Such properties have been addressed widely using different analysis techniques [2]-[5].

Recently, the stress effects on PCF for birefringence and confinement loss have been discussed [8]-[9]. However, the effects of external stress on the dispersion properties of PCF have not been reported yet in details.

In this work, the analysis of the effects of thermal and external stress on the propagation properties of PCF is carried out using finite element method (FEM). The effect of stress due to the variation of thermal expansion coefficients will be incorporated with the external stress from all sides. Under these conditions, the birefringence, modal confinement, and dispersion properties will be calculated and shown graphically.

II. METHODOLOGY

The FEM has been applied to carry out the modal solution of the PCFs. COMSOL Multiphysics [16] has been employed as a modelling tool, where a combination of structural mechanics module and electromagnetic module has been used to carry out the stress analysis and optical mode analysis of the PCF, respectively. Here, a simultaneous linear system of equations resulting from plane-strain approximation has been solved for nodal displacements. Because of the presence of stress on the fiber, the refractive index changes due to elasto-optic effect. With the new refractive index of the fiber material, optical analysis has been carried out to obtain modal effective refractive index. At the very outset, the model has been verified for its applicability and correctness by investigating a few parameters of an unstressed PCF and comparing the results with the published results [6].

III. MODAL SOLUTION OF SOLID CORE UNSTRESSED PCF

Figure 1(a) shows the schematic diagram of the full cross section of a PCF, consisting of four rings of arrays of air holes arranged in a silica background whose refractive index has been taken as 1.45 at a wavelength of 1550 nm. In the geometry shown, d is the hole diameter and Λ is the hole pitch of the PCF. It is assumed that the PCF is uniform in the longitudinal direction. Figure 1(b) shows the plot of power flow (time average, z -component) of fundamental mode, HE₁₁, of this unstressed ($P=0$) PCF. As expected the modal spot is confined in the central core region. The corresponding vector electric and magnetic field distributions are shown in Figure 2.

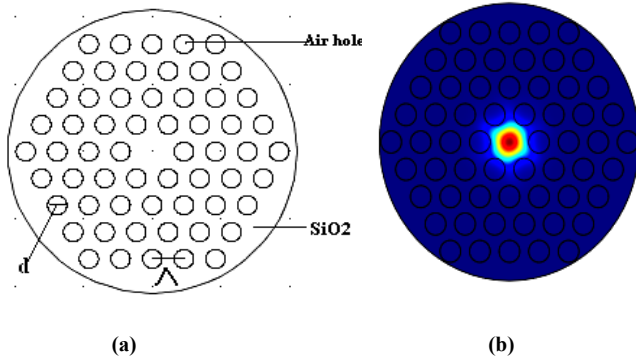


Figure 1. (a) Cross section of PCF, (b) power flow (time average, z component), of unstressed PCF, where $\Lambda=1.0 \mu\text{m}$ and $d/\Lambda=0.5$

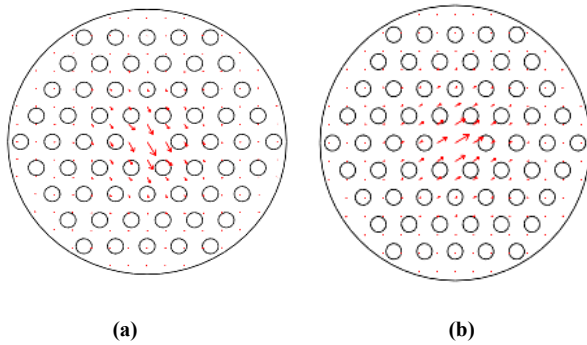


Figure 2. (a) Electric field, (b) Magnetic field of unstressed PCF

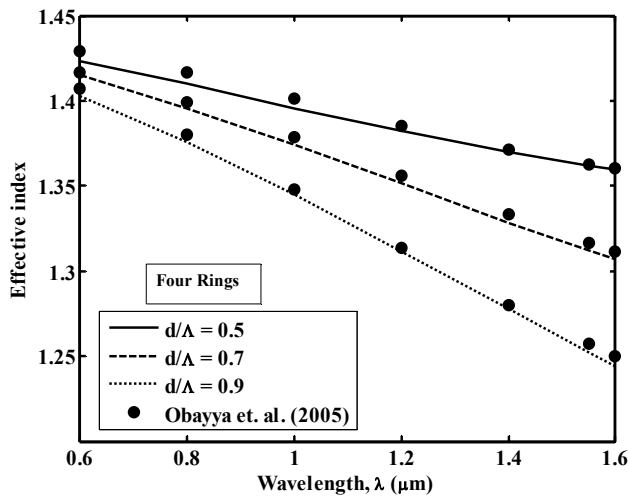


Figure 3. Variation of the effective index of a 4-ring unstressed PCF

Figure 3 shows the effective index, n_{eff} versus wavelength, λ for different values of d/Λ for the same unstressed PCF of Figure 1(a). The effective index steadily decreases as the wavelength is increased. The calculated results are compared with the same of [6]. Here the solid line, dashed line, and the dotted line show the results for $d/\Lambda=0.5, 0.7, 0.9$ respectively.

The dark circles show the results of Obayya et al. [6]. The results agreed very well.

IV. MODAL SOLUTION OF SOLID CORE PCF UNDER EXTERNAL STRESS

A specific geometrical structure of a solid core PCF is chosen to carry out the study and analysis here. The chosen PCF is having four rings of air holes with hole diameter $d=1.4 \mu\text{m}$, pitch $\Lambda=2.3 \mu\text{m}$ and over all diameter $D=10.5 \mu\text{m}$. Figure 4 shows the vector displacement over the cross section of the PCF under external stress with a maximum displacement of $7.335 \times 10^{-7} \text{m}$ and the minimum displacement $1.91 \times 10^{-9} \text{m}$. Thus, a deformation occurs over the cross section of the fiber and because of this deformation, there is a change in the refractive index, which can be seen in Figure 5.

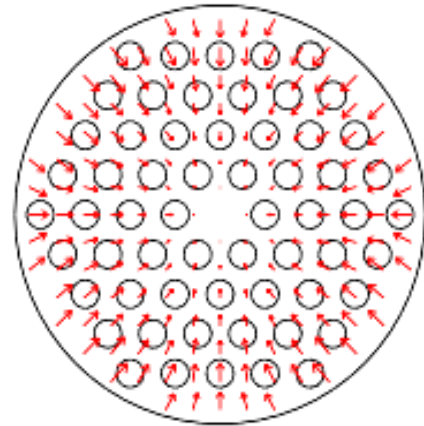


Figure 4. Vector displacement under external stress, where $P=4 \text{ GPa}$, $\lambda=1.55 \mu\text{m}$, $\Lambda=2.3 \mu\text{m}$, $d=1.4 \mu\text{m}$, and $D=10.5 \mu\text{m}$

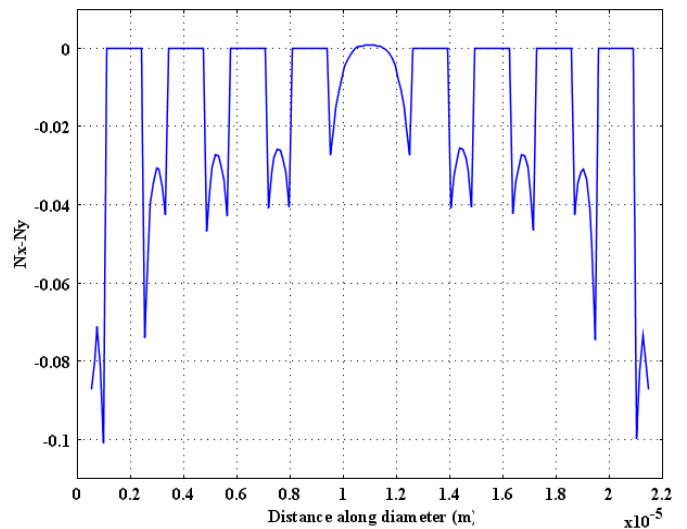


Figure 5. Change in refractive index along diameter of the PCF

The effect of stress on the refractive index also causes a change in the mode field distribution. For the fundamental x polarized mode, (H_{11}^x mode), the power flow as well as the corresponding electric and magnetic fields are shown in Figure 6.

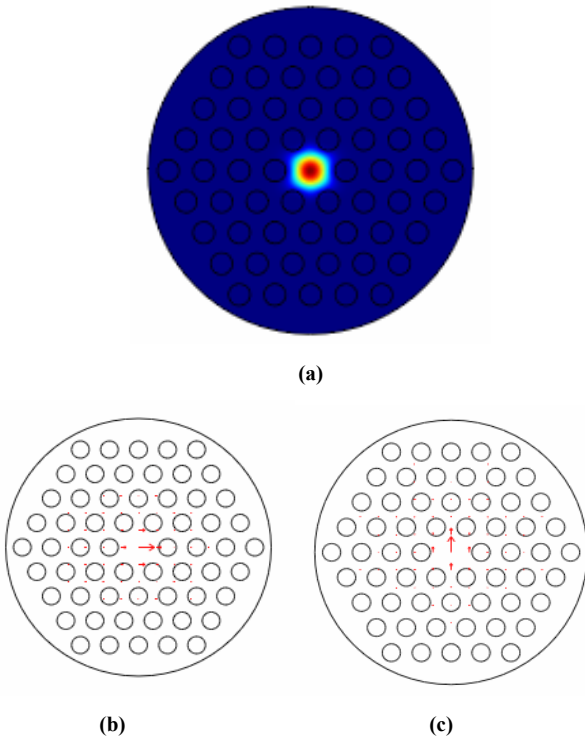


Figure 6. (a) Power flow, (b) vector E-field, (c) vector M-field, in a 4-ring PCF with $d=1.4\mu\text{m}$, $\Lambda=2.3\mu\text{m}$, $\lambda=1.55\mu\text{m}$ and $P = 4\text{ GPa}$

V. EFFECT OF STRESS ON REFRACTIVE INDEX AND BIREFRINGENCE

An unstressed (external stress $P=0$) PCF is considered and the fundamental propagation mode is found at each value of the varying wave lengths. Thereafter, pressure is applied uniformly from all directions. The external stress acting on the holey fiber induces a specific stress distribution in the fiber's cross section that makes the isotropic glass birefringent. The Figure 7 shows that the effective index, n_{eff} , over the operating frequency range (wavelength $0.7\mu\text{m}$ – $2.0\mu\text{m}$) decreases almost linearly. It is also evident from the plot that for both fundamental modes, n_{eff} increases with the increase of external stress.

Figure 8 shows the phase birefringence versus wavelength at different external stress conditions. As we know birefringence is the difference between the effective mode indices of two orthogonal polarization modes. The results show that the modal birefringence is smaller (of the order 10^{-5}), and is not shown in the figure when there is no external pressure ($P=0$). It is also revealed from the readings that birefringence remains almost flattened over the operating wavelength range at external pressures 1, 2 and 4

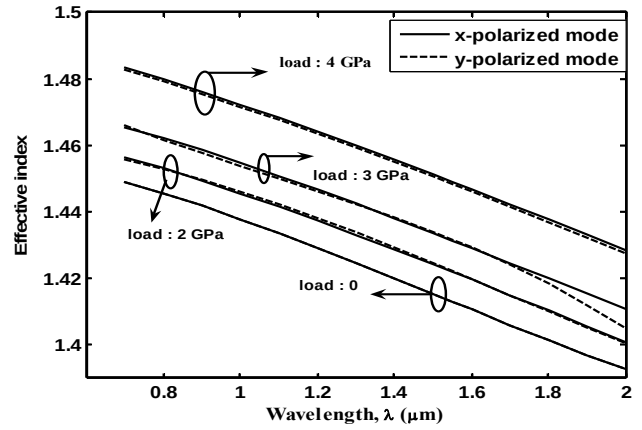


Figure 7. Effect of external stress on effective index and birefringence (4-ring PCF with $d=1.4\mu\text{m}$, $\Lambda=2.3\mu\text{m}$)

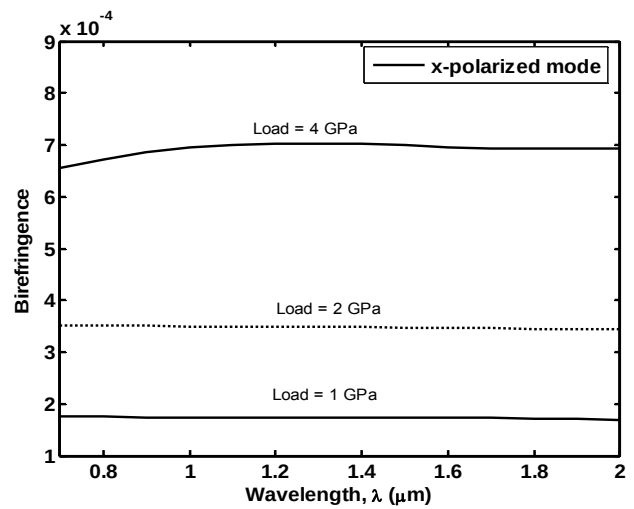


Figure 8. Phase birefringence versus wavelength (four-ring PCF with $d=1.4\mu\text{m}$, $\Lambda=2.3\mu\text{m}$) at different external pressure conditions

GPa. On the other hand, birefringence increases remarkably that reaches the order of 10^{-4} with the increase of uniform external pressure.

At zero pressure the modes are degenerate, but as load increases, the degeneracy gets lost and modal birefringence increases which become distinct at 4 GPa external pressure. In each experiment, effect of temperature (1000°C) has been taken into account. Here, the Sellmeier equation has been used to obtain the refractive index of different wavelengths and thus the material dispersion is included.

VI. EFFECT OF STRESS ON GROUP BIREFRINGENCE AND POLARIZATION MODE DISPERSION

The Figure 9 shows the group birefringence which is almost wavelength independent at zero external stress. But, it decreases almost linearly with the increase of the external stress over the operating wavelengths. The PMD is another source of limitation in PCF, and can be quantified from group

birefringence. The external stress acting on the holey fiber induces a specific stress distribution in the fiber's cross section and also deformation of the fiber's structure. Both factors have an effect on the phase and the group modal birefringence, and therefore, affect the PMD of the PCF.

The Figure 10 depicts the variation of PMD with the operating wavelength, λ at different external stress conditions. As the group birefringence is almost λ independent at zero external load, and its value is too small, so the value of PMD is also smaller and it is not shown here. The figure shows that PMD decreases almost linearly with the increase of wavelength. But it is interesting to observe that the rate of decrease of the PMD is higher at higher external stress.

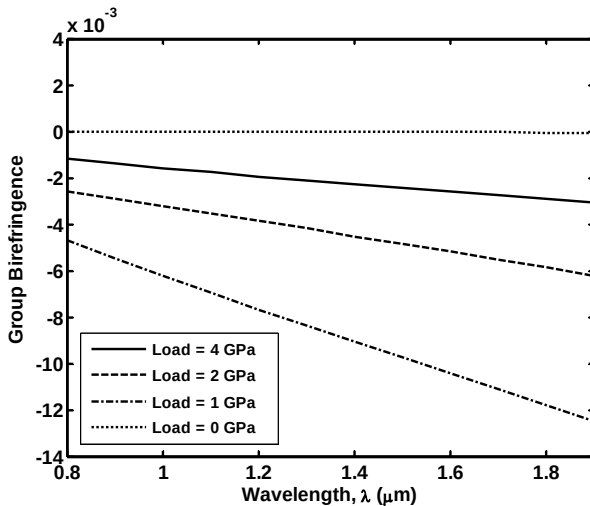


Figure 9. Group birefringence versus wavelength of 4-ring PCF with $d=1.4 \mu\text{m}$, $\Lambda=2.3 \mu\text{m}$ at different external stress conditions

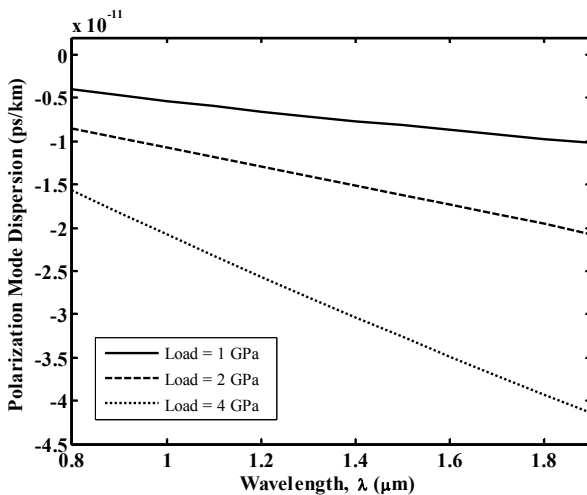


Figure 10. Variation of PMD in a 4- ring PCF, where $d=1.4 \mu\text{m}$ and $\Lambda=2.3 \mu\text{m}$, at various external stress

VII. EFFECT OF EXTERNAL STRESS ON DISPERSION

In single-mode fiber, the performance is primarily limited by chromatic dispersion (also called group velocity dispersion), which occurs because the refractive index of the glass material varies slightly depending on the wavelength of the light, and light from real optical transmitters necessarily has nonzero spectral width (due to modulation). PCFs possess the attractive property of great controllability in chromatic dispersion [1]-[5]. The chromatic dispersion profile can be easily controlled by varying the hole diameter, d and the hole pitch, Λ . For practical applications to optical communication systems, dispersion compensations, and nonlinear optics, controllability of chromatic dispersion in PCFs is a critical issue.

So far, various PCFs with significant dispersion properties have been studied and reported in [4]-[5]. But how do these properties of PCF get affected with the application of external stress still remains unaddressed. In this work, we have carried out detail study on the dispersion property of PCF under external stress conditions while taking into consideration the stress due to thermal effects.

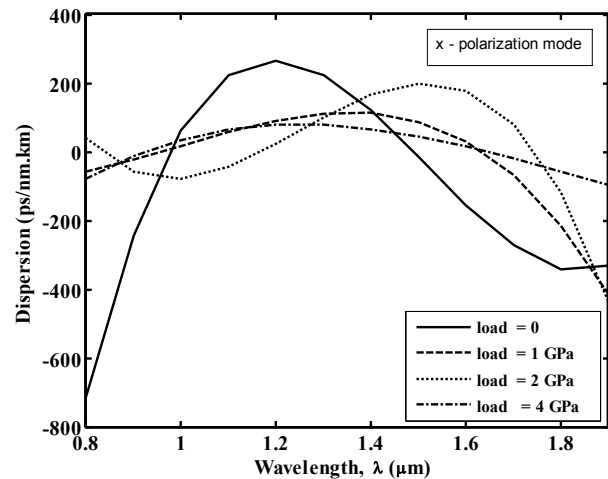


Figure 11. Variation of chromatic dispersion in a 4- ring PCF ($d=1.4 \mu\text{m}$ and $\Lambda=2.3 \mu\text{m}$) at various external stress

We have calculated the dispersion at various wavelengths and with variation of external applied force up to 4GPa. The graph shows that a flattened dispersion curve is possible at an external applied load of 2GPa over the wide operating wavelength. But at zero external load ($P=0$), the dispersion in the PCF shows anomalous reading which conforms to the results of normal PCF. PCFs at higher applied external pressure (4GPa, in this case), the dispersion again shows some anomalous readings. Thus it reveals that at specific value of external pressure the material of the PCF exhibits specific dispersion values. Thus, the PCF has got tremendous potential to be used as dispersion compensator devices in the field of telecommunications and other fields of applications.

VIII. CONCLUSION

In this work, a study and analysis have been carried out to evaluate various propagation properties of PCF considering thermal and external stress effects. External stress is applied from all directions to realize a hydrostatic pressure, and this causes deformation on the cross section of the PCF and the refractive index of the PCF material changes and becomes anisotropic. The phase birefringence increases with the increase in external stress over a wide operating wavelength. It is observed that the PMD decreases almost linearly with the increase in the external stress. Also, it is revealed from the results that flattened dispersion curve could be possible over a wide operating wavelength even under external stress. Furthermore, PCFs at specific external stress, show specific dispersion pattern and still they show the attractive property of great controllability of chromatic dispersion properties.

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