1. Introduction

Optical fiber sensors have become more favored due to their electromagnetic immunity, network compatibility, miniaturization, the aptitude for remote and the field of navigation. The emergence of photonic crystal fibers (PCFs) is a significant evolution in fiber optic technology, leading to a new properties that overcome many problems. Photonic crystal fibers are special types of fiber where air holes are arranged in a periodic nature in the cladding. Photonic crystal fibers guide the electromagnetic field by an arrangement of air holes that run down the entire fiber length. With the modulation of the location and size of the cladding air holes, the characteristics of photonic crystal fibers, such as transmission, birefringence, mode shape spectrum, dispersion and nonlinearity, could be tunable to manage the anticipated values. The existence of air holes provides the possibility to insert functional materials, the refractive index of which is dependent on external physical fields. This enables further dynamic modification of the waveguide properties and provides perspectives for various all-in-fiber tunable or sensing devices [1]. One of modern fiber optic applications in the field of navigation is an optical gyroscope. Optical gyroscope is based on the Sagnac effect, the time for light to travel in a coil is dependent of the rotation of the coil.

2. Analysis of published data and problem statement

Hollow core fiber photonics is based on microstructured fiber design using a photonic band gap (PBG) cladding composed of silica and air holes surrounding a hollow core for guiding. The photonic band gap guiding mechanism is fundamentally different from the traditional total internal reflection guiding principle in conventional fibers. Thanks to the flexibility for the cross section design, photonic crystal fibers (PCFs) [2] have achieved excellent properties in nonlinearity, birefringence, dispersion, single polarization single mode and effective mode area, and also excellent performances in the applications of fiber sensors [3], fiber lasers and nonlinear optics [4] over the past several years. Large numbers of research papers are highlighted some optical properties of the PCFs such as ultrahigh birefringence and unique chromatic dispersion, which are almost impossible for the conventional optical fibers. During the last decade, photonic crystal fibers (PCFs) have been extensively studied for various applications utilizing their unique capabilities such as tailored dispersion, endless single mode operation, suppressed optical nonlinearity and high birefringence [5, 6]. These unique features come from the fact that optical properties of the guided modes in the core can be easily manipulated by changing the air-hole structure in the cladding.

3 Purpose and objectives of the study

In this paper we proposed to use of a photonic crystal fiber in navigational guidance as optical gyroscope. There are many reasons made us think about this project. The following tasks were solved to reach the work purpose:

— The low nonlinearities. As more than 98 % of the mode is confined in air, not silica, the fibers are less sensitive to nonlinearities such as the Kerr effect.
— Pure silica material, with no co-dopants that can add to fiber environmental sensitivities.
— No Fresnel reflections at open fiber end when free-space coupling in air.
— The polarization maintaining design using form birefringence for low temperature sensitivity.
— Bending sensitivity is low compared with the conventional fibers. Fibers may be bent to very small diameters of less than 1 inch without added losses, thereby enabling smaller form factor designs.

4. Basic principles of fiber optical gyroscope

Fiber optical gyroscope is based on the Sagnac effect. Sagnac effect generates an optical phase difference ($\Delta \phi$) between two counter propagating waves in a rotating fiber coil [7]. Fig. 1 shows that fiber optic gyroscope is the simplest rotation sensors. They are widely used in commercial applications where their dynamic range and linearity limitations are not constraining.
During the rotation of angular velocity contour an apparent distance between points B and A for the oppositely traveling beams changes. For a wave traveling from point A to point B, i.e., in a direction similar to the direction of rotation of the contour, the distance is extended, as in a time dt point B moves to the angle \( \Delta \theta = \Omega \cdot dt \). Lengthening the path of the light beam is equal to dt, since at each instant the beam is directed at a tangent to the contour at that same tangential linear velocity directed projection \( \dot{\theta} = \ddot{\theta} \cdot \cos \alpha = \Omega \cdot t \cdot \cos \alpha \). Thus, the length of the path traversed by the beam is equal to \( DL + \dot{\theta} \cdot dt \).

Arguing similarly, for opposing traveling light beam will be a reduction in the apparent path segment \( Dl \). Considering the speed of light invariant quantity, apparent elongation and reduction paths for opposing beams can be considered equivalent to extensions and contractions of time intervals, i.e.:

\[
\Delta t_1 = \frac{1}{c} (\Delta l + \dot{\theta} \cdot dt).
\]

\[\text{(1)}\]

\[
\Delta t_1 = \frac{1}{c} (\Delta l - \dot{\theta} \cdot dt).
\]

\[\text{(2)}\]

If the relative time delays of counter propagating waves occurring during the rotation, expressed in terms of the phase difference of counter propagating waves, it will be:

\[
\Delta \phi = \omega \Delta t = \frac{4 \pi \alpha S}{c^2} \cdot \Omega = \frac{8 \pi \nu S}{c} \cdot \Omega = \frac{8 \pi S}{\lambda c}.
\]

\[\text{(3)}\]

where \( \omega = 2 \pi \nu \), \( \lambda = \frac{C}{\nu} \).

An optical fiber is used in the fiber optic gyroscope as the medium of propagation for the IR 1550 nm \( \lambda \). A long fiber cable is winded into loops in order to increase the effective area of the system. Two beams are again propagating through the fiber in opposite directions. Due to the Sagnac effect, the beam traveling against the rotation experiences a slightly shorter path delay than the other beam. Adversely affect the angle of rotation loop fiber optic gyroscopes and registered phase of the optical signal. These effects associated with the process of optical radiation propagation in the material of the optical medium, leading to a phase shift of counter propagating waves, which is not associated with the rotation of the closed loop. The negative effects are also associated with the processes of scattering and reflection of light in optical path, the polarization non-reciprocity effect associated with the asymmetric arrangement of anisotropic elements, relative to the centre of the fiber loop. This problem was solved by the use of frequency and phase modulation of the optical radiation is used, which allows to shift the zero point on the slope with the maximum slope of the interference signal. The resulting differential phase shift is measured through interferometry, thus moving one component of the angular velocity into a shift of the interference pattern which is measured photometrically.

5. Hollow-core photonic crystal fibers (HC-PCFs)

Hollow-core photonic crystal fibers are optical fibers with cladings made of glass incorporating arrays of air holes. The core is formed by omitting several unit cells of material from the cladding. The «holey» cladding has a two dimensional photonic band gap that can confine light to the core for wavelengths around a minimum-loss wavelength \( \lambda_c \), even when the core is hollow and filled with air [8]. In contrast, a conventional fiber guides light by total internal reflection so its core must have a higher refractive index than the cladding. Usually, this preform is then first drawn to a cane with a diameter of e.g. 1 mm, and thereafter into a fiber with the final diameter of e.g. 125 μm. Particularly soft glasses and polymers (plastics) also allow the fabrication of preforms for photonic crystal fibers by extrusion [9]. There is a great variety of hole arrangements, leading to photonic crystal fibers with very different properties. All these photonic crystal fibers can be considered as specialty fibers. In this paper used the fibers of the type Hollow Core photonic crystal fiber, 1550 nm, \( \Omega \) 10 μm, hollow core Photonic Bandgap Fibers guide light in a hollow core, surrounded by a microstructured cladding of air holes and silica. If the transverse scale of hollow-core photonic crystal fibres changes without otherwise changing the fibre’s structure, the wavelength \( \lambda_c \) of minimum attenuation must scale in proportion [10]. Without recourse to the approximations of the previous section, the mean square amplitude of the roughness component that couples light into modes with effective indices between \( n \) and \( n + \delta n \) is:

\[
u^2 = \frac{k_B T}{4 \pi^2 (n-n_0)} \coth \left( \frac{(n-n_0) k_B T}{2} \right) \delta n,
\]

where \( \gamma \) — the surface tension; \( k_B \) — Boltzmann constant; \( T \) — the temperature.

The attenuation to these modes is proportional to \( u^2 \) [11] but the only other independent length scale it can vary with is \( \lambda_c \). As attenuation has units of inverse length, it must therefore by dimensional analysis be inversely proportional to the cube of \( \lambda_c \). If this is true for every set of destination modes, it must be true for the net attenuation \( \alpha \) to all destination modes, so:

\[
\alpha(\lambda_c) = \frac{1}{\lambda_c^3}.
\]

\[\text{(5)}\]
The minimum optical attenuation of ~ 0.15 dB/km in conventional fibers is determined by fundamental scattering and absorption processes in the high-purity glass [12], leaving little prospect of much improvement. However, over 99% of the light in hollow-core — photonic crystal fibers can propagate in air [10] and avoid these loss mechanisms, making hollow-core photonic crystal fibers promising candidates as future ultra-low loss telecommunication fibers. The lowest loss reported in hollow-core photonic crystal fibers is 1.7 dB/km [10], though we have since reduced this to 1.2 dB/km. An understanding of the fundamental limitations to this loss is therefore of great importance. Since only a small fraction of the light propagates in silica, the effect of material nonlinearities is insignificant and the fibers do not suffer from the same limitations on loss as conventional fibers made from solid material alone.

6. Interferometer on photonic crystal fibers

The main argument in favor of a replacement of optical fiber to another medium is that the first Sagnac experiments conducted in the hollow pipe and the low pressure air is not observed effects are manifested in the optical fiber. In this regard, it is evident that the use of such optical media, which on the one hand, would allow optical radiation to channel, and on the other hand did not change to its frequency and phase characteristics. Such environments include photonic crystals with defects. The defect in such environments is a hollow waveguide. Manufactured photonic crystal fiber has a refractive index of 1.82 at wavelength 500 nm for this fiber type Kagome effective single-mode propagation occurs in a wavelength range (750–1050 nm) in diameter mainly 30 micro and loss of about 0.7 dB/m [13] see Fig. 3.

The collapsed zones in the PCF cause a broadening of the beam when it propagates from the SMF to the PCF [14]. The broadening of the beam combined with the axial symmetry and the modal properties of the PCF are what allow the excitation (and recombination) of modes that have similar azimuthal symmetry [15]. The modes excited in the PCF have different effective indices (or different propagation constants), thus, they move at different speeds. As a result, the modes accumulate a phase difference as they propagate along the PCF. Due to the excitation and recombination of modes in the device, the reflection spectrum is expected to exhibit a series of maxima and minima (interference pattern). When two modes participate in the interference the transmitted or reflected intensity (I) can be expressed as:

\[ I = I_1 + I_2 + 2\sqrt{I_1I_2}\cos(\Delta\Phi). \]  

(6)

In Equation (6) I1 and I2 are, respectively, the intensity of the core mode and the cladding mode and \( \Delta\Phi = 2\pi\Delta nL/\lambda \) is the total phase shift. \( \Delta n = n_f - n_c \), nf and nc being, respectively, the effective refractive index of the core mode and the cladding mode. L is the physical length of the PCF and \( \lambda \) the wavelength of the optical source. The fringe spacing or period (P) of the interference pattern is given by \( P = \lambda L/(\Delta nL) \). The maxima of the interference pattern appear at wavelengths that satisfy the condition:

\[ \Delta\Phi = 2m\pi, \]  

with \( m = 1, 2, 3\ldots \).

This means at wavelengths given by:

\[ \lambda_m = \Delta nL/m. \]  

(7)

![Fig. 2.](image)

Graphic: Minimum optical attenuation in hollow-core photonic crystal fibers. The solid orange curve shows the low-loss part of the measured attenuation spectrum of a 7-cell hollow-core photonic crystal fiber, with a minimum of 700 dB/km at \( \lambda_0 = 550 \) nm. (Left inset) Measured near-field pattern at the output of this fiber at 550 nm (points). The minimum attenuation of similar hollow-core photonic crystal fibers with various transverse scales, versus the wavelength \( \lambda_0 \) of minimum attenuation (broken red line). A straight-line fit is shown and has a slope of 3.07, supporting the predicted inverse cubic dependence in Equation (5).

![Fig. 3.](image)

Graphic: Example of photonic crystal fiber with a hollow core diameter of about 30 microns.
The fringe contrast or visibility \( V \) of a modal interferometer is an important parameter, particularly when the interferometer is used for sensing applications. Typically, higher visibility is desirable since it leads to larger signal-to-noise ratio and more accurate measurement. The visibility of a two-mode interferometer can be calculated by the well-known expression: \( V = (I_{\text{max}} - I_{\text{min}})/(I_{\text{max}} + I_{\text{min}}) \), where \( I_{\text{max}} \) and \( I_{\text{min}} \) are, respectively, the maximum and minimum values of \( I \) given in Equation (6). According to the definition and Equation (6) \( V \) can be expressed as [16]:

\[
V = \frac{2\sqrt{k}}{1 + k},
\]

where \( k = (I_1/I_2) \).

Many research groups prefer fringe contrast (expressed in dB) instead of visibility. The fringe contrast is defined here as \( FC = -10\log(1 - V) \). It can be noted that the fringe contrast increases as \( k \) approaches 6, i.e., when the two modes that participate in the interference have equal intensities. Fig. 4 shows the fringe contrast in a mode of interferometer as a function of \( k \) or the intensity of the cladding mode to that of the core mode ratio. The inset shows the theoretical reflection spectrum in the case of \( k = 0.4 \) (dotted line) and \( k = 0.96 \) (solid line).

The physical mechanism for the waveguide propagation of radiation in photonic fibers is not associated with the phenomenon of total internal and with the presence of the photonic band gap in the transmission spectrum of the fiber cladding. Waveguides of this type are promising for the creation of gas sensors, spectral elements, as well as laser-cooled atom management. Experimental studies have shown that in some cases [17]. Relatively high loss optical fibers with core air owing to scattering of light by irregularities of the glass surface due to the capillary waves Frozen. Solution to reduce optical loss photonic fibers requires further fundamental research, however, we can already use small pieces of photonic fibers in special measuring instruments, which include the fiber optic gyroscopes. Photonic crystal fiber is a two-dimensional photonic crystal structure based on the song «quartz glass-to-air» formed in the shell.

**7. Propagation of radiation in hollow core Photonic crystal defect**

In [18] were considered in detail the conditions of formation of photonic crystal fibers and spread them in the optical radiation. Experimental studies of PCF were conducted in a number of studies, for example, [19]. Photonic band gaps arising in the transmission spectrum of 2D periodic cladding, provides a high reflection coefficient for radiation propagating along the hollow core photonic crystal fibers, realizing mode waveguide propagation. In [19] the results of an experimental determination of the optical emission intensity distribution in the cross-sectional center of the defect and the results of numerical calculation of the distribution of power density in cross-section are given. These results are shown in Fig. 5.

![Fig. 4. Fringe contrast in a mode of interferometer](image)

**8. Discussion of the results**

The hollow core fiber offers a low reflectance interface, offering improved stability. Where designs require an alternative interface, such as a splice, mechanical coupling, or other type, reflections and mechanical integrity of the interface will need to be managed for hollow core fibers to realize their potential and advantages over conventional fibers in fiber optic gyroscopes. Long fiber lengths in a photonic crystal fibers gyroscope generally offer improved measurement sensitivity. The current loss levels of hollow core fibers designed for single mode transmission limit the fiber length. Although most of the light propagates in air, the portion that interacts with the silica hollow core wall experiences scattering and other loss mechanisms due to imperfections at this boundary. Fiber optic gyroscopes are...
gaining in addressing many of the markets traditionally dominated by mechanical and ring laser gyroscopes, in particular those used in navigation and guidance of aircraft and spacecraft where performance requirements are demanding. Within the area of fiber optic gyroscopes, the choice of fiber type can play a key role in determining the gyroscope capabilities. Advancements in photonic crystal fiber 1550 nm λ, ∅ 10 μm offer an attractive alternative to conventional silica core fibers.

9. Conclusion

Photonic crystal is one of the most promising platforms for optical information processing as it can enable compact and efficient photonic devices and also their large scale integration on-chip. In this paper we discusses of using hollow-core photonic crystal fibers, 1550 nm λ, ∅ 10 μm as part of the optical gyroscope. Hollow core photonic crystal fibers (HC-PCFs) are a type of fiber optics that present a diversity of new and improved features. Due to their unique geometric structure, HC-PCFs present special properties that lead to an outstanding potential for navigational guidance. The use of hollow core photonic crystal fibers instead of fiber in the conventional fiber optics will overcome many of the problems that are present in the conventional fibers.

References


ПРИМЕНЕНИЕ ФОТОНО-КРИСТАЛЛИЧЕСКИХ ВОЛОКОН В НАВИГАЦИИ

Волоконно-оптический гироскоп — это одна из сфер применения оптических волокон, зависящая главным образом от эффекта Саньяка. Область космической навигации является важной сферой применения волоконно-оптического гироскопа. В этой статье автор предложил использовать фотонно-кристаллическое волокно с полым сердечником 1550 нм λ, ∅ 10 мкм в оптическом гироскопе. Фотонно-кристаллические волокна демонстрируют специфические свойства и возможности, которые приводят к огромному потенциалу для использования в области навигации.

Ключевые слова: фотонно-кристаллическое волокно, эффект Саньяка, волоконно-оптический гироскоп, обычные волокна.