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The research on beat length of polarization maintaining optical fiber with external pressure

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ABSTRACT

Based on the coupled mode equations and elastic optic effect theory, the relationship between polarization maintaining fiber (PMF) beat length and external pressure was analyzed. Moreover, the beat length variation with different external pressure values F as well as angles θ between the pressure direction and PMF's x-axis was calculated numerically. The results demonstrated that the beat length variation was determined both by F and θ simultaneously. When F was a constant, the beat length was changed periodically in π cycle sinusoidal form with θ variation. Then, the minimum and maximum values of beat length would be obtained when θ were even and odd multiples of $\pi/2$, respectively. Meanwhile, the beat length variation was linear with F as θ was fixed. In this situation and with F increasing, if $\theta \in (k\pi + \pi/4, k\pi + 3\pi/4)$ $(k \in Z)$, the beat length would increase linearly; otherwise, the beat length variation would be in the opposite direction while $\theta \in (k\pi - \pi/4, k\pi + \pi/4)$ $(k \in Z)$; however, it remained almost unchanged in the case of $\theta = k\pi \pm \pi/4$ $(k \in Z)$. Finally, the beat length was measured with different pressure values F and angles θ based on a Sagnac interferometer system, and the results shown a great agreement with the theoretical analysis and simulation.

1. Introduction

Distributed optical fiber sensor, which is able to detect multi-parameters simultaneously and dynamically with high sensitivity, high spatial resolution and long distance, and also convenient to be implanted into the tested materials, has been playing an extremely important role in the structure health monitoring areas of bridges, dams, aerospace vehicles, large equipments, smart materials, and so on [1–3]. With the rapid development of sensing technology, the PMF has been widely used in the fiber sensing system [4,5]. For its better application in these systems, many researchers have investigated and analyzed the PMF structures and characteristics in recent years. Among them, Varnham had reported the calculation method of PMF internal stress distribution and birefringence in early 1983 [6]. Subsequently, Chu further analyzed the PMF thermal stress distribution and calculated the birefringence of PMF by using the geometric method and coupled mode theory [7]. Then, Galtarossa measured the beat length of several different single mode fibers accurately with experimental method in 2000 [8]. The PMF beat length measurement method based on a white light scanning Michelson interferometer was reported in 2012 [9,10], and the measurement accuracy was 0.019 mm. All the studies of PMF characteristics above have provided a theoretical foundation for its application in the fiber sensing areas. However, there were no papers which had ever analyzed and investigated the relationship between the beat length and external pressure systematically, and used the beat length variation of PMF to measure the external pressure quantitatively.

In this paper, the impact of external pressure on PMF beat length was analyzed systematically based on the coupled mode equations and elastic optic effect theory, and the beat length characteristics were simulated in numerical method under the condition of different pressure values F as well as angles θ between external pressure direction and x-axis of PMF. Finally, the beat length of Panda fiber was measured with the variation of F and θ based on a Sagnac interferometer loop system [11]. With the analysis of test results, it verified the validity of the theoretical analysis and numerical simulation.

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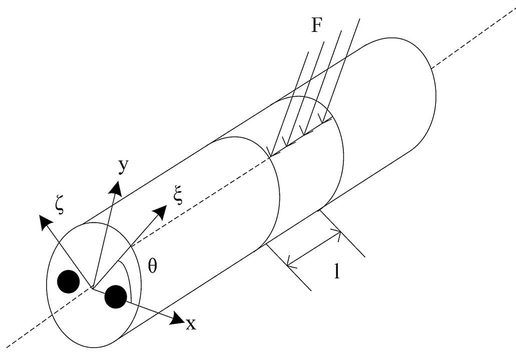

Fig. 1. PMF with external pressure.

2. Theory analysis

According to the coupled mode theory, if PMF is impacted by the disturbance of external pressure, the mode coupling will occur between two orthogonal polarization modes while they propagate along the PMF, and the propagation constant difference between the two main axes will be changed simultaneously [12,13], which will lead to the variation of birefringence and beat length of PMF. Here, the PMF with external pressure in Cartesian coordinate system is shown in Fig. 1 [14].

Where, θ is the angle between the external pressure direction and x-axis of Panda fiber, l is the interaction length of Panda fiber with external disturbance. Then, the electric field along x-axis and y-axis directions at the fiber output end can be written as following, respectively.

$$E_x = E_0[\cos\varphi\cos(\Delta\beta l/2) - i\cos(\varphi+\eta)\sin(\Delta\beta l/2)] \cdot \exp[-i(N_{xx}+N_{yy})l/2], \quad (1)$$

$$E_y = E_0[\sin\varphi\cos(\Delta\beta l/2) + i\sin(\varphi+\eta)\sin(\Delta\beta l/2)] \cdot \exp[-i(N_{xx}+N_{yy})l/2], \quad (2)$$

and,

$$\tan\ \eta = -2N_{xy}/(N_{xx}-N_{yy}), \quad (3)$$

where, E_0 is the amplitude of electric field, φ is the angle between the polarization direction of incident polarized light and the x-axis of Panda fiber, $\Delta\beta$ is the propagation constant difference of the two polarization directions in PMF, and N_{xx}, N_{yy} can be written as following [15,16]:

$$N_{ii} = \beta_0 + \omega\varepsilon_0 \int_s e_i^*[\Delta\varepsilon]e_i \mathrm{d}S \quad (i = x, y), \quad (4)$$

$$N_{ij} = N_{ji}^* = \omega\varepsilon_0 \int_s e_i^*[\Delta\varepsilon]e_j \mathrm{d}S \quad (i \neq j), \quad (5)$$

Here, β_0 is the propagation constant of PMF without external pressure, ε_0 is the dielectric constant in vacuum, ω is the angular frequency, e_x and e_y are the electric field vectors of two mutually orthogonal modes in the unperturbed PMF, respectively, * means complex conjugate.

And, $\Delta\beta$ can be determined by the following equation [14]:

$$\Delta\beta = \sqrt{(N_{xx}-N_{yy})^2 + |2N_{xy}|^2}, \quad (6)$$

When $\varphi = 0$, i.e. the polarization direction of the incident light and the x-axis are parallel. From Eqs. (1) and (2), the following equations can be obtained:

$$E_x = E_0\left[\cos(\Delta\beta l/2) - i\cos\ \eta\sin(\Delta\beta l/2)\right] \cdot \exp[-i(N_{xx}+N_{yy})l/2], \quad (7)$$

$$E_y = E_0\left[i\sin\ \ \eta\sin(\Delta\beta l/2)\right] \cdot \exp[-i(N_{xx}+N_{yy})l/2], \quad (8)$$

However, Eqs. (7) and (8) above are established in the x–y coordinate system. For the convenient calculation, we rotate the x–y coordinate system with angle θ and then can create a new ξ–ζ coordinate system. In this case, the dielectric tensor variation $[\Delta\varepsilon]$ can be written as:

$$[\Delta\varepsilon]_{\xi\zeta z} = \begin{bmatrix} \Delta\varepsilon_\xi & 0 & 0 \\ 0 & \Delta\varepsilon_\zeta & 0 \\ 0 & 0 & \Delta\varepsilon_z \end{bmatrix}, \quad (9)$$

where,

$$\Delta\varepsilon_\xi = 2n_0[c_1\sigma_\xi + c_2(\sigma_\zeta + \sigma_z)], \quad (10)$$

$$\Delta\varepsilon_\zeta = 2n_0[c_1\sigma_\zeta + c_2(\sigma_\xi + \sigma_z)], \quad (11)$$

$$\Delta\varepsilon_z = 2n_0[c_1\sigma_z + c_2(\sigma_\zeta + \sigma_\xi)], \quad (12)$$

Here, n_0 is the refractive index of fiber core; σ_ξ, σ_ζ and σ_z are the stress components which are induced by pressure F on the ξ, ζ and z directions; c_1 and c_2 are the elastic optic coefficients on the front and side of the stress surface element, respectively.

In the ξ–ζ coordinate system, because the fiber diameter is small enough, and the stress surface element can be seen as a rectangle approximately. According to the elasticity theory, the stress components of all directions on the cross section of PMF core can be approximated as following [17]:

$$\begin{cases} \sigma_\xi = -3F/l\pi d \\ \sigma_\zeta = F/l\pi d \\ \sigma_z = 0 \end{cases}, \quad (13)$$

In which, F is the positive pressure on the stress surface, l is the interaction length of PMF with pressure, d is the diameter of PMF.

When Eq. (9) is transformed into the x–y coordinate system based on matrix theory [18,19], and the variation of dielectric tensor $[\Delta\varepsilon]$ can be rewritten as:

$$[\Delta\varepsilon]_{xyz} = T^{-1}[\Delta\varepsilon]_{\xi\zeta z}T = \begin{bmatrix} \Delta\varepsilon_x & \Delta\varepsilon_{xy} & 0 \\ \Delta\varepsilon_{xy} & \Delta\varepsilon_y & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad (14)$$

And, the transformation matrix T is:

$$T = \begin{bmatrix} \cos\ \theta & \sin\theta & 0 \\ -\sin\ \theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad (15)$$

According to Eqs. (14) and (15), and the following results can be obtained:

$$\begin{cases} \Delta\varepsilon_x = \Delta\varepsilon_\xi\cos^2\ \theta + \Delta\varepsilon_\zeta\sin^2\ \theta \\ \Delta\varepsilon_y = \Delta\varepsilon_\xi\sin^2\ \theta + \Delta\varepsilon_\zeta\cos^2\ \theta \\ \Delta\varepsilon_{xy} = (1/2)(\Delta\varepsilon_\xi - \Delta\varepsilon_\zeta)\sin(2\theta) \end{cases}, \quad (16)$$

Therefore,

$$\Delta\varepsilon_x - \Delta\varepsilon_y = (8n_0F/l\pi d)(c_2 - c_1)\cos(2\theta), \quad (17)$$

$$\Delta\varepsilon_{xy} = (4n_0F/l\pi d)(c_2 - c_1)\sin(2\theta), \quad (18)$$

With Eqs. (17) and (18), then Eqs. (3) and (4) can be rewritten as [14]:

$$N_{xx} - N_{yy} = \frac{2\pi B}{\lambda} + \frac{8F}{ld\lambda}(c_2 - c_1)\cos(2\theta), \quad (19)$$

$$N_{xy} = \frac{4F}{ld\lambda}(c_2 - c_1)\sin(2\theta), \quad (20)$$