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Performance analysis for all-fiber polarization transformer with specific spun rate profile

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ABSTRACT

All-fiber polarization transformer (AFPT) is a length of variably spun birefringence fiber which can transform the state of polarization as a wave plate. A set of complete analytic solutions for the coupled-mode equation of AFPT with a specific function of spun rate is deduced by a modified method through deliberate matrix transformation. And the analytical expressions of the transmitting eigen-modes from the zero spun-rate end to the maximum spun-rate end are derived. Moreover, when the linear polarized light is input as single eigen-mode, the ellipticity of quasi-circular polarization light at the output end is calculated as function of the fiber structure parameters. The equivalent retardation of AFPT is evaluated and the critical constraints between the fiber length and the maximum spun rate are illustrated according to practical requirements.

1. Introduction

In optical fiber sensors, lasers and amplifiers, the state of polarization (SOP) of the light propagating along the fiber needs to be manipulated for optimal operation [1–3]. The transformation of SOP is usually controlled with bulk-optic wave plates which are bulky, narrowband, and often require careful manual adjustments. It has been demonstrated that a length of variably-spun birefringence fiber can function as a quarter-wave plate with wide band, if the spun rate increases slowly and the maximum rate is large enough [4–9]. When the linear polarization light is launched into the unspun-rate end as single eigen-mode, the quasi-circular polarization light can be obtained at the fast spun-rate end. This fiber element is usually called all-fiber polarization transformer (AFPT). AFPT can be not only made by the existing fabrication technique in a drawing tower with variably rotating preform [5], but also fabricated by post-draw twisting at the softening temperature of the fiber with shorter length [7].

The variably coupled-mode equation of AFPT has been discussed by Huang, who has given a set of approximate solutions by an iterative approach to predict its polarization transforming behavior [4]. Because the coupling coefficients are function of the spun-rate which varies along the whole fiber length, it is difficult to find analytical solutions for the coupled-mode equation. In conference of SPIE [10,11], we once reported our preliminary method by simple transformation matrix to find the analytic solutions based on assumption of constant and slowly variation factor. In this paper, through a set of more general transformation matrix which can directly diagonalize the coupled-mode equation, we give a modified method to find the specific function of spun rate which can make the equation possess analytical solutions. Then, in line with the analytical solutions corresponding to the specific spun-rate, the concise characteristics of AFPT are strictly predicted according to the fiber structure parameters. Meanwhile, the critical constraints between the fiber length and maximum spun-rate according to practical requirements are discussed in detail.

2. Transformation of coupled-mode equation in AFPT

The schematic diagram of AFPT is shown in Fig. 1. The spinning takes place gradually from the point of z=0. The rotation angle of local coordinates fixed with the linear birefringence axes at point z in fiber is $\varphi(z)$ and the profile of spinning rate is $\tau(z) = d\varphi/dz$.

In fabrication arts, the spun-rate profile is often taken as linear function $\tau(z) = \tau_L \cdot (z/L)$ or raised cosine function $\tau(z) = 0.5\tau_L [1 - \cos((z/L)\cdot\pi)]$, where L is the total length of the spun fiber and τ_L is the maximum spun rate at $z=L$.

In the local coordinates system, the electrical field components of light wave observe the polarization mode-coupled equation:

$$dA(z)/dz = K(z)A(z) \tag{1}$$

where $A(z)$ is a Jones matrix whose elements are $A_x(z)$ and $A_y(z)$ indicating respectively the electric field components along with the polarization principal axes of the birefringence fiber. Because the elastic-optical effect is encountered only for physical twist but not in the spun fiber which is drawn through melted state, the operator matrix

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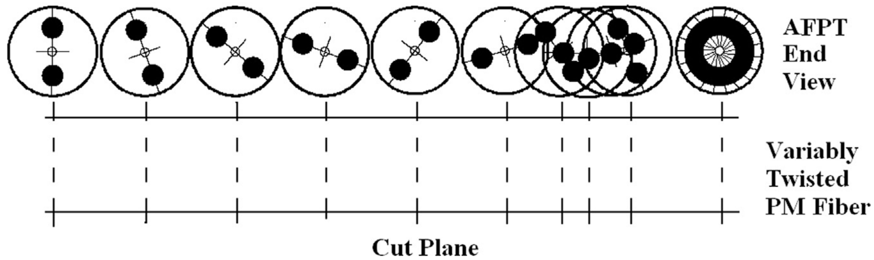

Fig. 1. The end view of a section of variably spun Panda birefringence fiber along the length.

K(z) of AFPT can be represented as [4].

$$K(z)=\begin{pmatrix} j\Delta\beta/2 & \tau(z) \\ -\tau(z) & -j\Delta\beta/2 \end{pmatrix} \tag{2}$$

where $\Delta\beta=\beta_x-\beta_y=2\pi/L_B$ is the difference between the propagation constants β_x and β_y respectively for the orthogonal polarized local modes in the birefringence fiber. L_B is the beat length of the prototypical birefringence fiber. For convenience, all the values concerned with length are normalized by the beat length L_B in the following. By the matrix transformation *A(z)=O(z)W(z)*, Eq. (1) can be changed as follows

$$dW(z)/dz=N(z)W(z) \tag{3}$$

$$N(z)=O^{-1}(z)\mathbf{K}(z)O(z)-O^{-1}(z)[dO(z)/dz] \tag{4}$$

$W(\mathbf{z})$ is also a column matrix, $W_x(z)$ and $W_y(z)$ are orthogonal components of the mode in normal coordinates. In order to diagonalize *K*(*z*), we choose the transformation matrix *O*(*z*) as follows

$$\mathbf{O}(z)=\begin{bmatrix} \cos\phi(z)\cos\theta-j\sin\phi(z)\sin\theta & \cos\phi(z)\sin\theta+j\sin\phi(z)\cos\theta \\ -\cos\phi(z)\sin\theta+j\sin\phi(z)\cos\theta & \cos\phi(z)\cos\theta+j\sin\phi(z)\sin\theta \end{bmatrix} \tag{5}$$

where $\phi(z)=0.5\arctan[2Q(z)]$, $Q(z)=\tau(z)/\Delta\beta=L_B\tau(z)/2\pi$ is the normalized spun-rate, θ is an undetermined constant independent of z. Substituting *O*(*z*), *K*(*z*) into Eq. (4), the operator matrix *N*(*z*) in normal coordinates can be derived as

$$N(z)=\left[j\frac{d\phi(z)}{dz}\right]\times\begin{bmatrix} \cos(2\theta)\frac{g(z)}{d\phi/dz}+\sin(2\theta) & -\cos(2\theta)+\sin(2\theta)\frac{g(z)}{d\phi/dz} \\ -\cos(2\theta)+\sin(2\theta)\frac{g(z)}{d\phi/dz} & -\cos(2\theta)\frac{g(z)}{d\phi/dz}-\sin(2\theta) \end{bmatrix} \tag{6}$$

where

$$g(z)=\pi\sqrt{1+4[Q(z)]^2} \tag{7}$$

and

$$\frac{d\phi(z)}{dz}=\frac{1}{1+4[Q(z)]^2}\frac{dQ(z)}{dz} \tag{8}$$

If $\theta=0$, from Eqs. (5) and (6), O(z) and N(z) are respectively equal to those in our previous conference reports [10,11]. So *O(z)* and *N(z)* in this paper are just the modified transformation matrix and general operator matrix. In general case for $\theta\neq 0$, the matrix N(z) can be directly diagonalized by choosing proper θ. Then we can determine the specific spun-rate profile according to θ and obtain the analytic solutions from matrix N(z).

3. Analytic solution for AFPT with specific spun-rate profile

If the sub diagonal elements of matrix *N*(*z*) are equal to zero, Eq. (3) may have analytical solutions. In order to diagonalize N(z) in Eq. (6), θ should satisfy

$$-\cos(2\theta)+\sin(2\theta)\frac{g(z)}{d\phi/dz}=0 \tag{9}$$

Substituting Eqs. (7) and (8) into Eq. (9), we obtain

$$\pi\tan(2\theta)=\frac{1}{\{1+4[Q(z)]^2\}^{3/2}}\frac{dQ(z)}{dz} \tag{10}$$

Suppose Q_L is the maximum normalized spun rate at the final end, that is when *z=L*, $Q(z)=Q(L)=Q_L=L_B\tau_L/2\pi$. For a determined Q_L and *L*, by definite integration with *Q(0)=0* and *Q(L)=*Q_L, the proper θ and the corresponding specific function of normalized-spun-rate can be derived as

$$\theta=\frac{1}{2}\arctan\left\{\frac{Q_L}{\pi L\sqrt{1+4Q_L^2}}\right\} \tag{11}$$

$$Q(z)=\frac{Q_L}{\sqrt{\left(\frac{L}{z}\right)^2(1+4Q_L^2)-4Q_L^2}} \tag{12}$$

The corresponding spun rate profile is

$$\tau(z)=\frac{\tau_L}{\sqrt{\left(\frac{L}{z}\right)^2+4\left(\frac{L_B\tau_L}{2\pi}\right)^2\left[\left(\frac{L}{z}\right)^2-1\right]}} \tag{13}$$

Eq. (6) can be simplified by Eq. (9) as follows

$$N(z)=\left(j\frac{d\phi(z)}{dz}\right)\begin{bmatrix} \csc(2\theta) & 0 \\ 0 & -\csc(2\theta) \end{bmatrix} \tag{14}$$

By the integration of Eqs. (3) and (14) respectively, we obtain

$$W(z)=\exp\left[\int_0^z N(t)dt\right]W(0) \tag{15}$$

$$\int_0^z N(z)dt=j\begin{bmatrix} \csc(2\theta) & 0 \\ 0 & -\csc(2\theta) \end{bmatrix}\int_0^z\frac{d\phi(t)}{dt}dt=[j\phi(z)]\begin{bmatrix} \csc(2\theta) & 0 \\ 0 & -\csc(2\theta) \end{bmatrix} \tag{16}$$

Substituting Eq. (16) into Eq. (15) yields

$$W(z)=\begin{bmatrix} \exp[j\phi(z)\csc(2\theta)] & 0 \\ 0 & \exp[-j\phi(z)\csc(2\theta)] \end{bmatrix}W(0) \tag{17}$$

This is the analytic solutions of the coupled-mode Eq. (3) in normal coordinates. The eigen-modes at z=0 are $W_1(0)=[1,0]^T$ or $W_2(0)=[0,1]^T$, and the transmitting eigen-modes along fiber can be written respectively as $W_1(z)=[1,0]^T\exp[j\phi(z)\csc(2\theta)]$ or $W_2(z)=[0,1]^T\exp[-j\phi(z)\csc(2\theta)]$.

Considering the modified transformation A(z)=O(z)W(z), the analytic solutions of the coupled-mode Eq. (1) can be deduced from Eq. (17) as follows