Optik 127 (2016) 5035–5039

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Theoretical study on the stability of practical polarization transformers

Xiao Yue-yu*, Yang Hui-xiang

Key Laboratory of Specialty Fiber Optics and Optical Access Networks, Shanghai University, Shanghai 200072, China

ARTICLE INFO

Article history:
Received 26 August 2015
Accepted 18 January 2016

Keywords:
Fiber polarization transformers
Optical current transformers
Coupling efficiency
Polarization stability

ABSTRACT

Stability of practical polarization transformer (PPT) proposed by Huang is studied for the application of all-fiber optical current transformers (AFOCTs). The previous zero-order approximate solution ignores inter-mode coupling, which is one of the factors causing AFOCT instability. This paper develops a concise approximate solution to take into account the coupling between two local eigen-modes in the PPT. It is shown that power exchange of the two modes is determined by the internal coupling coefficient. Guidelines for designing spin rate profiles are given and verified with numerical results.

1. Introduction

Over the past 20 years, all-fiber optical current transformer (AFOCT) as a candidate of a next generation device for high voltage measurement has received significant attention [1,2]. The all fiber quarter wave-plate (AFQW) is a key component in an AFOCT system. AFQW can interconvert between linearly polarized lights and circularly polarized lights. A commonly used AFQW is a short polarization maintaining (PM) fiber whose birefringent axes are set to 45° with respect to the axes of interconnecting PM fibers. The length of the retarder is several integers plus a quarter of the fiber beat length. The beat length, however, is susceptible to environmental changes, resulting in a scale factor error of the AFOCT system [3]. Huang proposed a polarization transformer by spinning a PM fiber with a slowly varying spin rate from zero to fast, termed *practical polarization transformer* (PPT), which outperforms conventional fiber retarders in terms of stability, and therefore can improve the long-term stability of AFOCT systems [4,5]. Unlike conventional AFQW, PPT is a single local eigen-mode excitation device from one end to the other, making the state of polarization (SOP) transformations less dependent on wavelength and temperature. PPT was also termed by Rose et al. as *polarization-transforming fiber* [6].

Some theoretical analysis, modeling calculation and experimental research works have been performed on this variably spun birefringence fiber. When the intrinsic structure satisfies the basic criteria, the ellipticities can reach to 0.9 for the linear-in, circular-out (LICO) case and 0.002 for the circular-in, linear-out (CILO) case, respectively [7]. However, in the application of high-precision AFOCTs, the stability of the transformed SOP by a PPT is also crucial. The inter-mode coupling in a PPT, which is ignored by the zero-order approximation [8], is an important cause of the instability of the AFOCT system.

In this work, a concise first-order approximate solution that takes into account coupling between the two local eigen-modes in the PPT is obtained. The factors affecting the coupling efficiency of the two modes are analyzed, and guidelines for designing spin rate profiles are given. It is found that a stable output SOP of the PPT, and a stable scale factor of the AFOCT system built upon it, can be obtained by a careful design of the spin rate profile, instead of increasing the length of the device.

2. Physics of PPT

PPT is fabricated by spinning a PM fiber preform at a slowly varying spin rate, or by post-draw twisting of a PM fiber at a softening temperature. In a PPT, the orthogonal birefringence axes rotate along the fiber core at a slowly increasing rotation rate, as shown in Fig. 1. On the left end, the spin rate is zero, while on the right end the birefringent axes are fast-spun with several rotations within a beat length of the un-spun PM fiber.

Coupling between the two linear polarization modes along the birefringent axes is governed by a coupled-mode equation [4]:

$$\frac{\mathrm{d}}{\mathrm{d}z}\begin{bmatrix} A_x \\ A_y \end{bmatrix} = \begin{bmatrix} j\Delta\beta/2 & \xi(z) \\ -\xi(z) & -j\Delta\beta/2 \end{bmatrix}\begin{bmatrix} A_x \\ A_y \end{bmatrix} \quad (1)$$

* Corresponding author. Tel.: +86 02169982382.
E-mail address: yyx@staff.shu.edu.cn (X. Yue-yu).

http://dx.doi.org/10.1016/j.ijleo.2016.01.135
0030-4026/

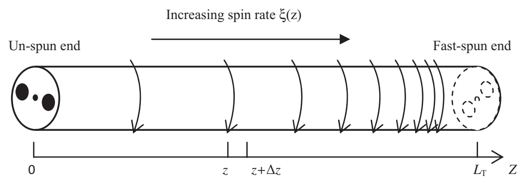


Fig. 1. Schematic of a PPT.

where, A_x and A_y are the amplitudes of the two linear polarization modes along the birefringent axes, $\Delta\beta$ the phase-velocity difference between the two modes, and $\xi(z)$ the position-dependent spin rate. For the entire device, the local eigenstates are not invariable as the spin rate varies as a function of position z:

$$\begin{cases} E_1(z) = \left[\dfrac{\xi(z)}{\sqrt{\xi^2(z) + \left[g(z)+\Delta\beta/2\right]^2}}, j\dfrac{g(z)+\Delta\beta/2}{\sqrt{\xi^2(z) + \left[g(z)+\Delta\beta/2\right]^2}} \right]^T \\ E_2(z) = \left[j\dfrac{g(z)+\Delta\beta/2}{\sqrt{\xi^2(z) + \left[g(z)+\Delta\beta/2\right]^2}}, \dfrac{\xi(z)}{\sqrt{\xi^2(z) + \left[g(z)+\Delta\beta/2\right]^2}} \right]^T \end{cases} \tag{2}$$

where,

$$g(z) = \sqrt{\xi^2(z) + \left(\Delta\beta/2\right)^2} \tag{3}$$

The eigenstates at the un-spun end are two linearly polarized lights along the birefringence axes, $E_{1u}(z) = [0,1]$ and $E_{2u}(z) = [1,0]$. At other positions, they are two orthogonal elliptically polarized lights. At the fast spun end, where, $\xi(z) \gg \Delta\beta/2$, they become two orthogonal circularly polarized lights: $E_{1f}(z) = [1, j]/\sqrt{2}$ and $E_{2f}(z) = [j, 1]/\sqrt{2}$. To describe the polarization evolution, a super-mode theory based on the local eigenstates is developed [8]:

$$\frac{dW(z)}{dz} = N(z)W(z) \tag{4}$$

where, $W(z) = [W_1(z), W_2(z)]^T$ is an amplitude vector of the local eigenstates $E_1(z)$ and $E_2(z)$, and

$$N(z) = \begin{bmatrix} jg(z) & -jQ(z) \\ -jQ(z) & -jg(z) \end{bmatrix} \tag{5}$$

$$Q(z) = \frac{\Delta\beta}{\left(\Delta\beta\right)^2 + 4\xi^2(z)} \cdot \frac{d\xi(z)}{dz}. \tag{6}$$

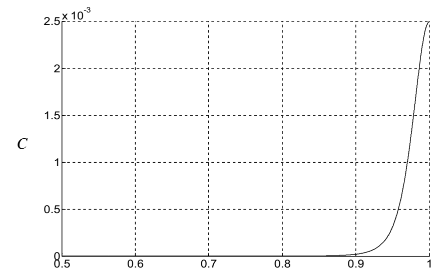
3. Approximate analytical solution of coupling

Eq. (4) does not have an exact closed-form solution since the spin rate $\xi(z)$ is variable. A zeroth-order approximate solution is presented in [8], in which energy exchange between the two local eigenstates is ignored. However, when the slow variation condition $d\xi(z)/dz \approx 0$ is not satisfied, coupling cannot be ignored. The coupling can be analyzed numerically, for example, using the transfer matrix method (TMM). The transfer matrix $M(n\Delta z)$ at position $n\Delta z$ is:

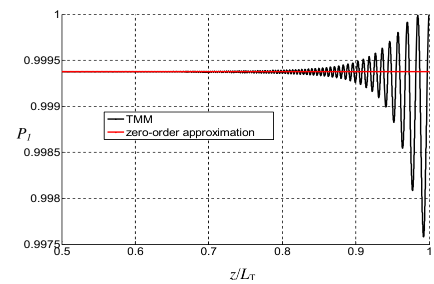
$$M(n\Delta z) = \begin{bmatrix} \cos(\gamma_n\Delta z) - j\dfrac{g_n}{\gamma_n}\sin(\gamma_n\Delta z) & -\dfrac{jQ_n}{\gamma_n}\sin(\gamma_n\Delta z) \\ -\dfrac{jQ_n}{\gamma_n}\sin(\gamma_n\Delta z) & \cos(\gamma_n\Delta z) + j\dfrac{g_n}{\gamma_n}\sin(\gamma_n\Delta z) \end{bmatrix} \tag{7}$$

where, $\gamma_n = \sqrt{g_n^2 + Q_n^2}$. Therefore, the amplitude vector of the local eigenstates is obtained:

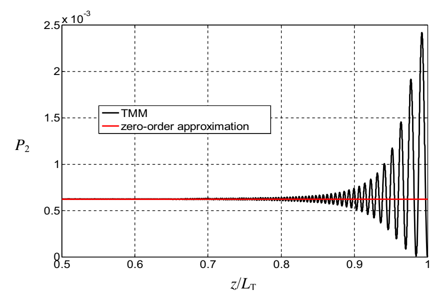
$$\begin{bmatrix} W_1(N\Delta z) \\ W_2(N\Delta z) \end{bmatrix} = M_N \begin{bmatrix} W_1(0) \\ W_2(0) \end{bmatrix} \tag{8}$$



(a) Distribution of coupling coefficient along the PPT



(b) Power evolution in the major local eigenstate along the PPT



(c) Power evolution in the minor local eigenstate along the PPT

Fig. 2. Coupling coefficient distribution and power evolutions along the PPT.

where the total transfer matrix is

$$M_N = \prod_{n=1}^{N} M(n\Delta z) \tag{9}$$

The off-diagonal entries in the transfer matrix represent the coupling. Thus, we define a coupling coefficient at $n\Delta z$ as

$$C_n = \left(Q_n/\gamma_n\right)^2 \tag{10}$$

Assume a right-hand circularly polarized (RHCP) light is injected into the fast spun end. Let the linearly decreasing spin rate be described by $\xi(z) = \xi_{max}[1 - z/L_T]$, the maximum spin rate $\xi_{max} = 10{,}000$ rad/m, the phase-velocity difference $\Delta\beta = 1000$ rad/m, and the length of PPT $L_T = 400$ mm. Using TMM, a numerical solution to Eq. (4) can be obtained as shown in Fig. 2, in which (a) depicts the coupling coefficient distribution from the fast spun end to the zero-spun end, and (b) and (c) show the power evolutions of E_1 and E_2, respectively ($P_1 = |W_1|^2$, $P_2 = |W_2|^2$). From these plots, we observe that power in the two local modes is not constant as indicated by the zeroth-order approximation. Towards the zero-spun end, as the coupling coefficient rises steeply, power coupling between the two modes becomes increasingly striking, and exhibits an oscillating pattern.