A novel spin profile for low polarization mode dispersion

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Theoretical basis of spun fibers and their ability to reduce Polarization Mode Dispersion (PMD) are discussed. In order to overcome PMD-based problems, Amplitude Modulation Transmitted Carrier (AM-TC) profile is proposed. A comparative analysis of spin profiles is made and spin parameters giving successful results for low-PMD fibers are obtained. Simulation results show that for spin period of *1 m* and spin amplitude of *2.76 turns/m*, the proposed AM-TC spin profile provides better PMD reduction results than the conventional ones. For different modulation index values of the AM-TC spin profile, the differential group delay (DGD) obtained is under *1.4 fs*.

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1. Introduction

In perfectly circular single mode optical fibers, light travels as two degenerate modes with orthogonal polarizations. Due to some imperfections, e.g. perturbations in circular symmetry, fiber stress, bending, twist etc., these two orthogonal modes propagate with different phase velocities. The transmission delay between two modes is called differential group delay (DGD) [1], [2], which is a kind of pulse spreading effect, and it leads to dispersion called polarization mode dispersion (PMD). PMD is widely studied as a performance limiting issue [2]–[8].

Researchers have focused on two main research areas to reduce the detrimental effects of high PMD in optical fiber communication systems. One of the research areas is based on compensating PMD in installed fiber using different techniques [9]. The other method is based on designing and producing low-PMD fibers. This second method has recently been realized by spinning the transmission fiber [10]. The spinning is a part of manufacturing process that is done by applying an appropriate amount of torque to the fiber as it is drawn from preform. This torque may have a constant rate in one direction or a variable rate in both directions. The spinning process shortens the birefringence correlation length by forcing the slow and fast axes to rotate, leading to a low PMD value in fiber [11], [12].

This study discusses the theory behind PMD in spun fibers and presents a new spin profile to achieve low PMDs using spinning process. Second section reviews the coupled mode theory of orthogonal polarization modes for understanding PMD. In the third section, fiber spinning process is explained and a novel Amplitude Modulation – Transmitted Carrier (AM-TC) spin profile is introduced to reduce the PMD effects in the fiber and this method is compared with the conventional profiles.

2. Theory

The light propagating in the transmission fiber has two orthogonally polarized modes. These modes experience same phase velocities in perfectly circular fibers. However, in real fibers this circularity is not perfect due to some intrinsic or extrinsic constructional perturbations. Thus, orthogonal polarization modes propagate at different speeds in the fiber so they are called as slow and fast modes.

The electric field under perturbations in the fiber can be considered as a linear combination of the electric fields for two orthogonally polarized modes as

$$\mathbf{E}(x,y,z)=\sum_{n}A_n(z)\mathbf{e}_n(x,y)e^{-i\beta z}, \quad n=1,2 \quad (1)$$

where $\boldsymbol{e}_n(x,y)$ is the electric field distribution, $n=1, 2$ shows two orthogonal polarization modes. Without perturbations in the fiber, two modes propagate with the same propagation constant β. $A_n(z)$ are the complex coefficients representing the electric field amplitudes of modes [13]. Complex electric field amplitudes $A_1(z)$ and $A_2(z)$ of the spun fiber can be described by using the coupled mode equation as

$$\frac{d}{dz}\mathbf{A}=i\kappa\mathbf{A} \quad (2)$$

where κ is a 2×2 coupling coefficient matrix. This matrix is given by

$$\kappa=\begin{pmatrix} 0 & \frac{1}{2}\Delta\beta e^{2i\int_0^z \alpha(z')dz'} \\ \frac{1}{2}\Delta\beta e^{-2i\int_0^z \alpha(z')dz'} & 0 \end{pmatrix} \quad (3)$$

where $\Delta\beta$ is the birefringence of the fiber and $\alpha(z)$ is the spin profile function. One can get the Jones matrix by integrating (2) with initial conditions of $A_1(0)=1$ and $A_2(0)=0$ as

$$J(z)=\begin{pmatrix} A_1(z) & -A_2^*(z) \\ A_2(z) & A_1^*(z) \end{pmatrix} \quad (4)$$

The PMD of a spun fiber can be obtained from Jones matrix as [14]

$$PMD=\frac{2}{L}\sqrt{\left|\frac{dA_1(z)}{d\omega}\right|^2+\left|\frac{dA_2(z)}{d\omega}\right|^2} \quad (5)$$

where L is the length of the fiber and ω is the angular frequency of the light. One can get the DGD of a spun fiber using (5) as

$$\tau(z)=\tau_\omega\left|\int_0^z e^{-2i\Theta(z')dz'}\right| \quad (6)$$

where $\Theta(z)=\int_0^z \alpha(z')dz'$. Eq. (6) shows the DGD of a spun fiber, where $\tau_\omega = d(\beta_s-\beta_f)/d\omega$ is the DGD of an unspun fiber. β_s and β_f are propagation constants for slow and fast modes respectively and ω is the angular frequency of light [14], [15].

3. Modelling the spinning process

For simplicity, let's consider that the birefringence in the fiber is constant and fiber is divided into short segments. The fast axis of one segment is aligned with the slow axis of the following segment. Thus, the DGD of one segment is compensated with the DGD of the second segment [12], [15].

The effectiveness of the spinning process on PMD reduction is defined with PMD reduction factor *PMDRF*, which is the ratio between the DGD of spun (τ) and that of unspun fibers (τ_ω) [16].

$$PMDRF=\frac{\tau}{\tau_\omega} \quad (7)$$

DGD of an unspun fiber as a function of the position in the fiber is given as $\tau_\omega(z)=2\pi z/(\omega L_B)$ where ω is the angular frequency of light, which is related to the speed of light and the operating wavelength as $\omega=2\pi c/\lambda$. L_B is the beat length of the fiber, which can be described as the propagation distance where a 2π phase difference accumulates between the slow and fast axes. The standard telecommunication fibers have a beat length value of ~10 m [12]. A lower PMDRF means a higher effectiveness in PMD reduction by a certain spinning process. Bidirectional spinning means the fiber is alternately spun clockwise and counterclockwise with a periodical spin function. In this method we need the parameters of spin amplitude α_0 and the spin period p to define the spin profile.

A sinusoidal spin function can be defined as $\alpha(z)=\alpha_0\cos(2\pi z/p)$ where α_0 is the spin amplitude, p is the spin period and z is the position in the fiber. Fig. 1 shows three spin profiles. Besides conventional sinusoidal and Amplitude Modulation – Suppressed Carrier (AM-SC) spin profiles [14], [16], the proposed AM-TC profile can be analyzed using the analytical model given with (6).

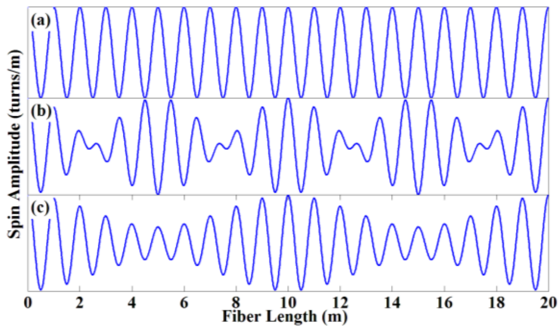

Fig. 1. The three spin profiles (a) Sinusoidal (b) AM-SC, (c) AM-TC with modulation index μ=0.5

The AM-SC spin profile takes the form

$$\alpha(z)=\alpha_0\cos(2\pi z/p)\cos(2\pi f_m z) \quad (8)$$

while AM-TC can be expressed with the function

$$\alpha(z)=\alpha_0\left[1+\mu\cos(2\pi f_m z)\right]\cos(2\pi z/p) \quad (9)$$

where f_m is the message frequency and μ is the modulation index of the spinning function. DGD of a spun fiber can be obtained by substituting the related spin function in (6). PMD reduction ability of spin profiles are analyzed using (7).

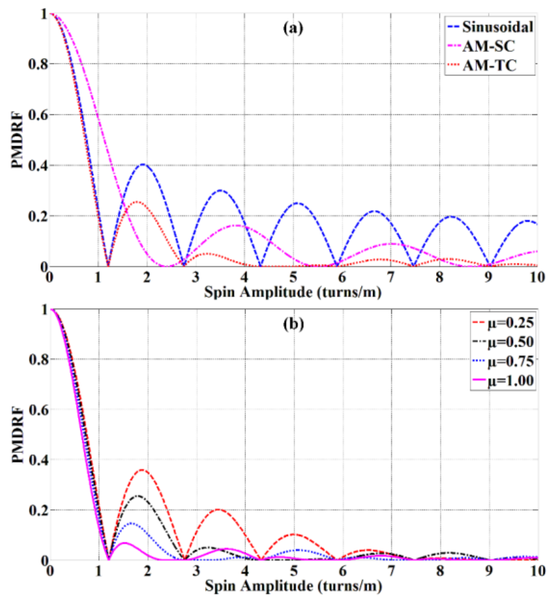

Fig. 2. PMDRF variation as a function of spin amplitude. Spin period is 1 m for all spin profiles. (a) PMDRF comparison of sinusoidal, AM-SC and AM-TC spin profile (b) PMDRF comparison of AM-TC spin profile for different modulation indices

PMD reduction abilities of different spin profiles have been simulated using MATLAB. The parameters used in the simulations are a beat length L_B of *10 m*, a fixed spin period *p of 1 m*, an operating wavelength λ of *1550 nm*, a carrier frequency $fc=(1/p)$ of $1\ m^{-1}$ and a message frequency f_m of $0.01\ m^{-1}$. The criterion used in choosing these parameters is its applicability. The modulated spin profiles shown in Fig. 1 need rapid changes in the direction of spinning. Therefore, the spin period has been chosen to be appropriate for practical applications. Also, f_m has to be much smaller than f_c to form an appropriate amplitude modulation [13], [14]. Fig. 2 shows the PMDRF as a function of spin amplitude for three different profiles and different modulation indices. Fig. 2(a) shows a comparative PMDRF analysis for sinusoidal, AM-SC and AM-TC spin profiles, where the AM-TC function has a modulation index of *0.5*. According to simulation results one may choose $\alpha_0=2.76$ *turns/m*, $\alpha_0=2.38$ *turns/m* and $\alpha_0=2.76$ *turns/m* for sinusoidal, AM-SC and AM-TC spin profiles respectively to achieve near zero PMDRF. Fig. 2(b) shows simulation results for AM-TC spin profile with different modulation indices. Using a modulation index varying from 0.25 to 1.00, the near zero PMDRF can be achieved for a wide range of spin amplitude. *2.76 turns/m* spin amplitude is a useful value for the AM-TC spin profile for low PMDRF. The modulation index μ of AM-TC is also an important parameter for low PMDRF. In simulations modulation index μ has been increased from *0.25* to *1.00* with *0.25* increments. With increasing μ, the PMD reduction has occurred for a wider range of spin amplitude, e.g. for $\mu=1$ a low PMD is provided for spin amplitudes in the range of *4.33 turns/m - 10 turns/m*.

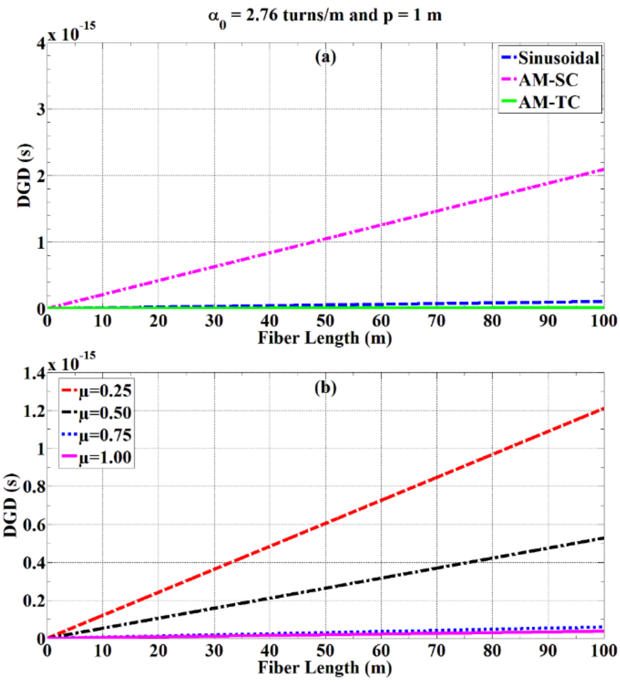

Fig. 3. DGD variation as a function of fiber length from 0 to 100 m (a) Comparison of different spin profiles (b) Comparison of AM-TC for different modulation indices

In Fig. 3 the PMD reduction ability of conventional and proposed spin profiles has been shown with DGD vs. fiber length graphics. Simulations have been carried out for fiber lengths from *0* to *100 m*. Fig. 3(a) shows a comparative analysis of DGD variation for different spin profiles for $\alpha_0=2.76$ *turns/m*, *p=1 m*, $f_m=0.01\ m^{-1}$ and $\mu=0.75$ spin parameters. All profiles have low DGD values under *2.5 fs*. The proposed spin profile AM-TC has the lowest DGD values. In Fig. 3(b) the DGD of AM-TC spin profile is compared for different values of modulation index μ. One can see from Fig. 3(b) that with increasing μ values a lower DGD value can be obtained. For all μ values the DGD is under *1.4 fs*.

Another parameter affecting the PMDRF is the spin period. PMDRF variations as a function of both the spin amplitude and the spin period are shown in

Fig. 4 for three spin profiles. As it can be seen in the 3D plots, PMDRF shows an oscillatory decreasing characteristic with increasing spin amplitude and spin period.

Fig. 4(c) shows that for a wider range of spin amplitude and spin period, PMDRF remains at low values for the proposed AM-TC spin function.

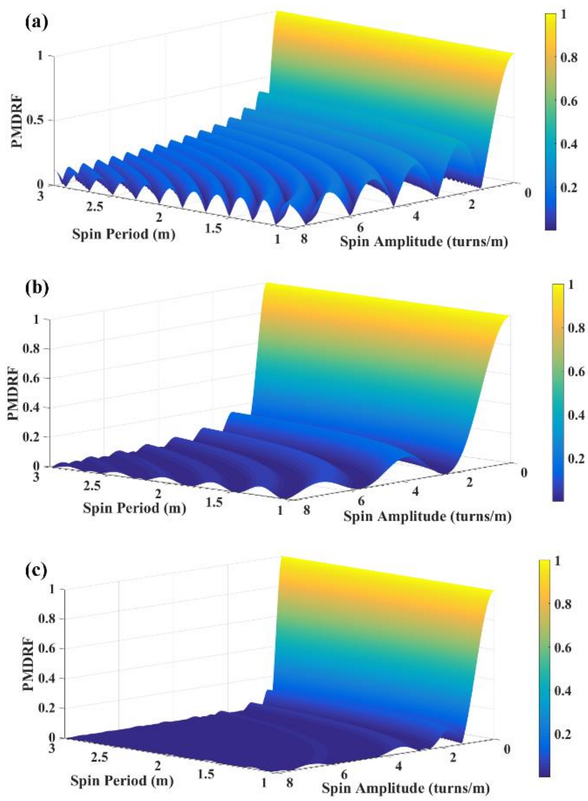

Fig. 4. PMDRF variations with respect to spin amplitude and spin period (a) Sinusoidal (b) AM-SC (c) AM-TC (μ=0.5) spin profiles

4. Conclusion

Spinning the fiber during the drawing process is an efficient method to get low-PMD fibers. With the analytical approach, PMD reduction abilities of several spin profiles are discussed in this paper. Besides conventional spin profiles, AM-TC profile is also proposed with this study. The amplitude and period of spin function is crucial for effective PMD reduction. Based upon simulation results, $\alpha_0=2.76$ *turns/m* and $p=1$ *m* may be chosen as spin parameters for AM-TC profile. Also results show that modulation index of AM-TC function is an important parameter. With increasing μ values, better PMD reduction has been provided. The simulations in this study have been performed for short length of fibers. Our following studies are going to focus on the statistical evolution of PMD and optimizing the spinning process in long length of fibers. It is expected that the optimum spin parameters can be obtained for the fibers having ultra-low PMDs with different spin profiles in long length of fibers.

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