Spin effect on a single-mode single-polarization optical fiber

Minning Ji (季敏宁)[1,*], Gang-Ding Peng[2], and Yanhua Luo[2]

[1]*Institute of Fiber Optics, Key Laboratory of Specialty Fiber Optics and Optical Access Networks, School of Communication and Information Engineering, Shanghai University, Shanghai 201800, China*

[2]*School of Electrical Engineering and Telecommunications, University of New South Wales, NSW 2052, Australia*

**Corresponding author: jmn2001@shu.edu.cn*

Received July 9, 2014; accepted November 28, 2014; posted online February 9, 2015

The spin effect on a single-mode single-polarization optical fiber is investigated theoretically and numerically. To get a practical single elliptically polarized fiber the normalized spin rate must be in the range of 0.2–0.35. A single elliptically polarized fiber with a normalized spin rate around 0.224 is demonstrated. It has a broad band from 1.530 to 1.558 μm, in which the low-leakage elliptically polarized eigenmode loss is kept within 1.2 dB while the high-leakage elliptically polarized eigenmode loss is greater than 20 dB. This fiber can be used as an elliptical polarizer or applied in current sensing.

OCIS codes: 060.2270, 060.2420, 060.2310.

doi: 10.3788/COL201513.020602.

Since the 1980s a variety of spun fibers have been fabricated and studied, such as the spun low-birefringence fiber[1,2] that is utilized to reduce the polarization mode dispersion and the spun high birefringent (Hi–Bi) elliptically polarized fiber[3,4] that is applied for current sensing. The twisted optical fiber[5] and the helical fiber[6] can lead to circular birefringence and they are used for circularly polarized light transmission. In recent years, a new version of spun fiber called the chiral fiber has appeared[7–9]. Its spin pitch is much shorter than the spun Hi–Bi and is usually about several hundred micrometers. It shows a peculiar property in that it can transmit only one of the circularly polarized states[8]. No matter what kind of structure they are or how they are fabricated, all these fibers have a common characteristic in that the corresponding un-spun fiber is a single-mode fiber with two orthogonally linear polarized states. What will happen if the corresponding un-spun fiber is replaced by a single-mode single-polarization (SMSP) fiber, in which only one of linear polarized states can transmit properly and the orthogonal one is cut off because of the leakage loss? Can we acquire a single elliptically polarized or even a single circularly polarized fiber by spinning the SMSP fiber? A spun SMSP fiber was reported many years ago[10]. A single elliptically polarized fiber with an extinction ratio around 10 dB/m was acquired[10]. The ellipticity was also estimated approximately. How to describe the light propagation and the limitation of this kind of fiber were not presented. This Letter will focus on these problems and will give a comprehensive investigation. First, the equation describing the mode coupling and light propagation is established. Then some numerical results are demonstrated to illustrate the propagation property and the application limits. Last, a specified spun single elliptically polarized fiber is presented and the corresponding spin effect with a different wavelength and a different spin rate is shown. The characteristics of the spun SMSP fiber are thoroughly analyzed.

It is well-known that the equation describing light transmission in a spun birefringent fiber is as follows[11]

$$\frac{dE}{dz} = TE, \tag{1a}$$

$$E = \begin{pmatrix} E_x \\ E_y \end{pmatrix}, \tag{1b}$$

$$T = \begin{pmatrix} i\frac{\delta\beta}{2} & \tau \\ -\tau & -i\frac{\delta\beta}{2} \end{pmatrix}, \tag{1c}$$

where E_x and E_y represent the electric field amplitude of the x-direction polarized and y-direction polarized light (respectively) under the local axes which are spinning along the fiber, $\delta\beta = \beta_x - \beta_y$, β_x and β_y are the propagation constants of the x-direction polarized mode and y-direction polarized mode (respectively) in the un-spun fiber, spin rate $\tau = \frac{2\pi}{\Lambda}$, and Λ is the spin pitch of the spun fiber. The common factor $e^{i(\beta_x+\beta_y)z/2}$ related to the electric field E has been ignored.

In an SMSP optical fiber, one of the linear polarized modes is cut off, while the orthogonal mode is guided[12]. If we designate the y-direction polarized mode as the cut-off one, the corresponding propagation constant will be a complex, i.e., $\beta_y + \alpha i$, where β_y is the real part and α is the imaginary part that represents the leakage loss coefficient of the cut-off mode. Then Eq. (1a) is extended as

$$\frac{dE}{dz} = \begin{pmatrix} i\frac{\beta_x-\beta_y}{2} & \tau \\ -\tau & -i\frac{\beta_x-\beta_y}{2} - \alpha \end{pmatrix} E. \tag{2}$$

This is the light-transmission equation in spun SMSP optical fibers (i.e., spun SMSP) under local reference axes.

It is derived by us based on coupled mode theory. If the following matrix transformation is introduced into Eq. (2), i.e.,

$$E = \mathbf{O}w, \tag{3}$$

where w is the supermode,

$$\mathbf{O} = \begin{bmatrix} \cos(\phi) & i\sin(\phi) \\ i\sin(\phi) & \cos(\phi) \end{bmatrix}, \tag{4a}$$

$$\phi = \frac{1}{2}\arctan\left(\frac{2\tau}{\delta\beta - i\alpha}\right), \tag{4b}$$

or

$$\tan(\phi) = \sqrt{\left(\frac{\delta\beta - i\alpha}{2\tau}\right)^2 + 1} - \frac{\delta\beta - i\alpha}{2\tau}, \tag{5}$$

then

$$\frac{dw}{dz} = \begin{bmatrix} ig - \alpha/2 & 0 \\ 0 & -ig - \alpha/2 \end{bmatrix} w, \tag{6a}$$

$$g = \sqrt{\tau^2 + \left(\frac{\delta\beta - i\alpha}{2}\right)^2}. \tag{6b}$$

The eigenmodes under local reference axes are elliptically polarized and are orthogonal to each other, i.e.,

$$w_x = \begin{pmatrix} 1 \\ 0 \end{pmatrix} e^{igz - \frac{\alpha}{2}z} E_x = \begin{bmatrix} \cos(\phi) \\ \sin(\phi)i \end{bmatrix} e^{igz - \frac{\alpha}{2}z}, \tag{7a}$$

$$w_y = \begin{pmatrix} 0 \\ 1 \end{pmatrix} e^{-igz - \frac{\alpha}{2}z} E_y = \begin{bmatrix} \sin(\phi)i \\ \cos(\phi) \end{bmatrix} e^{-igz - \frac{\alpha}{2}z}. \tag{7b}$$

It should be noted that the constant g is not a real number; it is a complex number. From Eqs. (7a) and (7b) we can see that the ellipticity of the two eigenmodes is determined only by the factor $\left[\begin{smallmatrix} \cos(\phi) \\ \sin(\phi)i \end{smallmatrix}\right]$ or $\tan(\phi)$. By some complicated deduction we can get the following result

$$\begin{bmatrix} \cos(\phi) \\ \sin(\phi)i \end{bmatrix} \to \begin{bmatrix} 1 \\ \tan(\phi)i \end{bmatrix} \to \begin{pmatrix} 1 \\ \rho e^{i\varphi} \end{pmatrix} \to \begin{pmatrix} 1 \\ e^{i\Phi} \end{pmatrix}, \tag{8a}$$

$$\rho = \left|\sqrt{\left(\frac{\delta\beta - i\alpha}{2\tau}\right)^2 + 1} - \frac{\delta\beta - i\alpha}{2\tau}\right|, \tag{8b}$$

$$\varphi = \frac{\pi}{2} + \arctan\left[\frac{\mathrm{Im}\left(\sqrt{\left(\frac{\delta\beta - i\alpha}{2\tau}\right)^2 + 1} - \frac{\delta\beta - i\alpha}{2\tau}\right)}{\mathrm{Re}\left(\sqrt{\left(\frac{\delta\beta - i\alpha}{2\tau}\right)^2 + 1} - \frac{\delta\beta - i\alpha}{2\tau}\right)}\right], \tag{8c}$$

$$\tan(\Phi) = \frac{\sin(\varphi)}{\sqrt{\cos(\varphi)^2 + \left(\frac{\rho^2 - 1}{2\rho}\right)^2}}. \tag{8d}$$

The ellipticity ϵ that represents the ratio between semi-minor axis b and semi-major axis a of the elliptically polarized state of the eigenmode is

$$\epsilon = \frac{b}{a} = \tan\frac{\Phi}{2}. \tag{9}$$

The leakage loss coefficient of the first eigenmode E_x is

$$\alpha_x = \mathrm{Im}\left[\sqrt{\tau^2 + \left(\frac{\delta\beta - i\alpha}{2}\right)^2}\right] + \frac{\alpha}{2}. \tag{10}$$

The leakage loss coefficient of the second eigenmode E_y is

$$\alpha_y = -\mathrm{Im}\left[\sqrt{\tau^2 + \left(\frac{\delta\beta - i\alpha}{2}\right)^2}\right] + \frac{\alpha}{2}. \tag{11}$$

It can be seen that the eigenmode E_y is high-loss while the eigenmode E_x is low-loss. If there is no spin, the leakage loss coefficient corresponding to eigenmode E_x is zero and the leakage loss coefficient corresponding to eigenmode E_y is α. If the fiber is high-spun, i.e., $\tau \gg \delta\beta$ and α, or in another words the spin pitch Λ of the fiber is far shorter than the beatlength $L_b = \frac{2\pi}{\delta\beta}$, the leakage loss coefficients corresponding to the two orthogonal polarization states approach the same value $\frac{\alpha}{2}$. If the spin rate is intermediate, the leakage loss coefficient corresponding to eigenmode E_y is higher than the leakage loss coefficient corresponding to eigenmode E_x. The former one is above $\frac{\alpha}{2}$ while the later one is below $\frac{\alpha}{2}$, but their sum is equal to α and is invariant with the spin rate. Considering that the ellipticity of the two orthogonal eigenmodes E_x and E_y is identical to each other, we designate the elliptically polarized E_y as the high-leakage one and the elliptically polarized E_x as the low-leakage one. The extinction ratio η between these two elliptically polarized eigenmodes is

$$\eta = -40\log(e) L\,\mathrm{Im}\left[\sqrt{\tau^2 + \left(\frac{\delta\beta - i\alpha}{2}\right)^2}\right], \tag{12}$$

where L represents the spun fiber length, and the extinction ratio unit is dB. The leakage loss ratio between the high-leakage eigenmode and low-leakage eigenmode is

$$HL = \frac{\alpha_y}{\alpha_x} = \frac{-\mathrm{Im}\left[\sqrt{\tau^2 + \left(\frac{\delta\beta - i\alpha}{2}\right)^2}\right] + \frac{\alpha}{2}}{\mathrm{Im}\left[\sqrt{\tau^2 + \left(\frac{\delta\beta - i\alpha}{2}\right)^2}\right] + \frac{\alpha}{2}}. \tag{13}$$

From Eq. (12) it can be seen that the extinction ratio η decreases in accordance with increasing spin rate τ. If the fiber is high-spun, the extinction ratio will approach zero. To acquire a practical elliptically polarized optical fiber there must be a compromise between the high extinction ratio and high ellipticity; high ellipticity means high-spun and a low extinction ratio.

To illustrate the spin effect on SMSP fibers some numerical results are shown in Figs. 1–5. To be more general, the spin rate τ and leakage loss coefficient α are normalized by $\delta\beta$, or equivalently the length quantity, such as spin pitch Λ, is normalized by beatlength $L_b = \frac{2\pi}{\delta\beta}$. In Figs. 1 and 3–5, the solid line corresponds to $\alpha = 10^{-6}$, the dotted line corresponds to $\alpha = 0.1$, the dashed line corresponds to $\alpha = 0.5$, and the dash–dot line corresponds to $\alpha = 1$.

From Fig. 1 it is evident that the ellipticity of the elliptically polarized eigenmodes always increases with the spin rate increase, no matter the leakage loss coefficient α being large or small. The only difference is that too large of a leakage loss coefficient α will result in decreased ellipticity. However, in a practical SMSP fiber, the leakage loss coefficient α is much smaller than $\delta\beta$. The normalized leakage coefficient α is much smaller than 1. Consequently, the ellipticity error resulting from a different leakage loss coefficient α can be neglected. The ellipticity can be approximated by that corresponding to $\alpha \cong 0$ as is shown by the solid-line in Fig. 1 and can be expressed as

$$\epsilon = \sqrt{1 + \left(\frac{\Lambda}{2L_b}\right)^2} - \frac{\Lambda}{2L_b}. \qquad (14)$$

In Fig. 2 it is shown that the loss of the high-leakage elliptically polarized eigenmode decreases with the spin rate increase while the low-leakage one is increased. When the spin rate is high enough the leakage loss of the two elliptically polarized eigenmodes will approach each other. Their difference will disappear and the extinction ratio will be equal to zero when the spin rate is close to infinity.

In Fig. 3 the extinction ratio between the two elliptically polarized eigenmodes is demonstrated. Although there is a little difference with the different leakage coefficient α, as is shown by the dashed line or dash–dot line with $\alpha = 0.5$ or $\alpha = 1$, respectively, the extinction ratio always decreases with the spin rate increase. In a practical spun SMSP fiber, α is much smaller than 1. It is usually about 0.1 or smaller. Consequently, the extinction ratio difference resulting from different α parameters can be

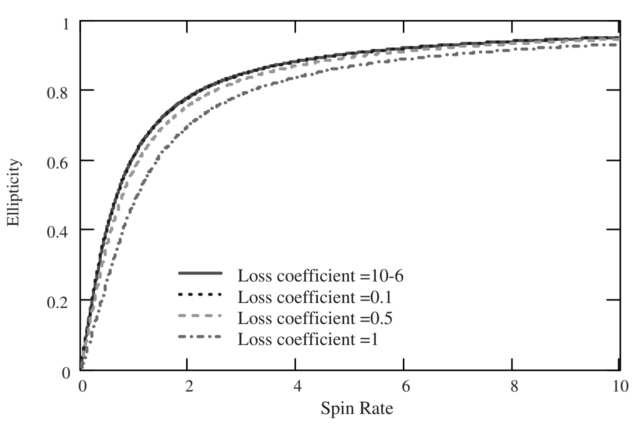

Fig. 1. Ellipticity in a spun SMSP fiber.

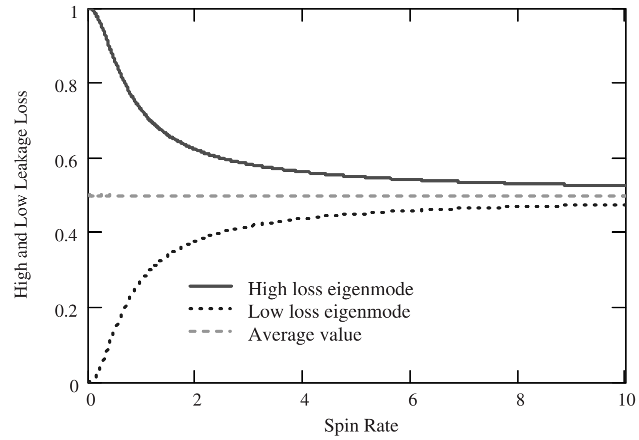

Fig. 2. Leakage loss of the elliptically polarized eigenmodes in a spun SMSP with $\alpha = 0.1$. Leakage loss is normalized by the cut-off mode leakage loss α of the un-spun fiber.

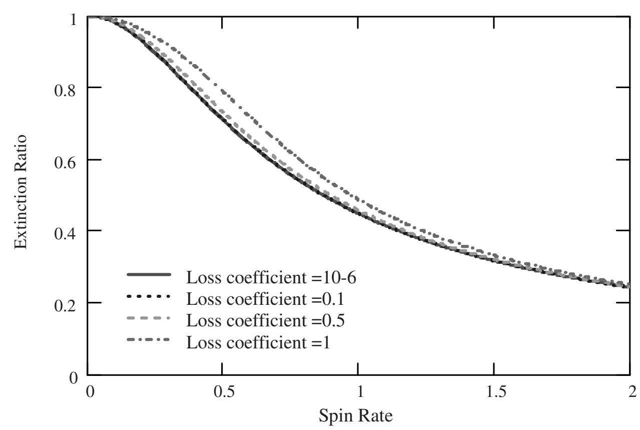

Fig. 3. Extinction ratio in a spun SMSP fiber. Extinction ratio is normalized by the un-spun fiber.

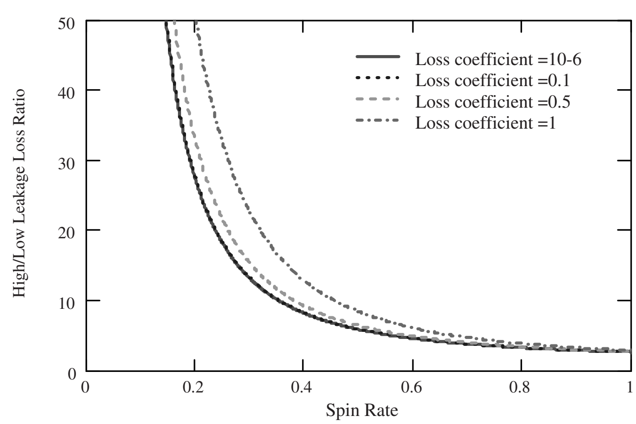

Fig. 4. Loss ratio between high-leakage and low-leakage elliptically polarized eigenmodes in a spun SMSP fiber.

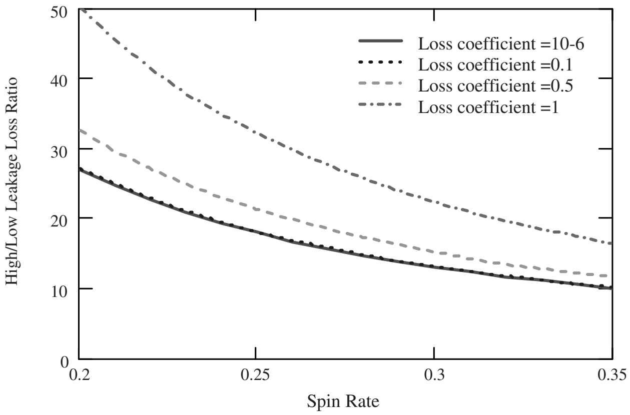

Fig. 5. Loss ratio between high-leakage and low-leakage elliptically polarized eigenmodes with a normalized spin rate ranging from 0.2 to 0.35.

neglected. The extinction ratio can be approximated by the solid line of Fig. 2. It should be noted that the extinction ratio has been normalized by that corresponding to the un-spun SMSP fiber [i.e., 20 $\log(e)L\alpha$].

From Figs. 1–3 we can see that to acquire high ellipticity the spin rate should be large enough, but this will result in too small of an extinction ratio because of the averaging effect of the two elliptically polarized eigenmodes. To get an appropriate extinction ratio the spin rate should be elected as a moderate one. We should also note that the un-normalized extinction ratio, as is shown by Eq. (12), is dependent on fiber length. If the fiber length is long enough the absolute extinction ratio will be large enough, but at the same time the leakage losses of the two elliptically polarized eigenmodes will be so large that they cannot propagate in the spun fiber. To cope with this problem a new parameter that represents the loss ratio between the two elliptically polarized eigenmodes is introduced in Eq. (13). This HL parameter is useful in describing the extinction ability and transmission property of the spun SMSP fiber. As is shown in Fig. 4, this HL ratio decreases with the spin rate increase. There is also some difference with the different leakage loss coefficient α. A spun fiber with large α can enhance the HL ratio, which is shown by the dashed line or the dash–dot line with $\alpha = 0.5$ or $\alpha = 1$, respectively. In a practical fiber α is much smaller than 1. The HL ratio can be approximated by the solid line in Fig. 4.

From an application viewpoint, HL ratio should be large enough that the low-leakage eigenmode can transmit well while the high-leakage eigenmode is extinguished. Usually this ratio should be larger than 10. If the ratio is less than 10 the loss of the low-leakage one will have to be more than 2 dB to acquire a 20 dB extinction ratio. From Fig. 4 the possible range of the normalized spin rate should be smaller than 0.35 if the HL ratio is larger than 10. On the other hand, the spin rate cannot be too small; otherwise the ellipticity will be too small to be used for current sensing applications (and so on). In Fig. 5 the HL ratio graph is drawn again with the normalized spin rate ranging from 0.2 to 0.35. As is seen the loss ratio between the high-leakage eigenmode and low-leakage eigenmode is larger than 10 when the spin rate is in the related region. When the normalized spin rate is at 0.2 the HL ratio will be close to 27, which means that the minimum extinction ratio can be as large as 26 dB if the loss of low-leakage eigenmode is 1 dB or more.

When the spin rate is in the range of 0.2–0.35 the ellipticity is between 0.193 and 0.315. The relative current sensitivity is between 13.8% and 32.9% [deduced from Eq. (12) in Ref. [4]). If the spin rate is equal to 0.25, or the spin pitch of the spun SMSP fiber is just four times the beatlength of the un-spun SMSP fiber, the ellipticity of the eigenmodes will be 0.236, and the relative current sensitivity will be 20%. At the same time, the HL ratio is close to 18. This kind of fiber can be applied in current sensing or used as an elliptical polarizer.

An SMSP fiber[12–14] is specifically designed for spun SMSP. As is shown in Fig. 6, this fiber is composed of three layers: the circular core with highest refractive index n_c (its radius is c), the elliptical stress element inner cladding with depressed refractive index n_s (its semi-major and semi-minor axes are a and b, respectively), and the outer cladding with intermediate refractive index n_{cl}. To simplify the problem the outer cladding is supposed to be extended to infinity. The structure parameters are elected as $c = 4$ μm, $b/c = 3$, $a/b = 2.5$, $n_{cl} = 1.459$, $n_c^x = 1.462$, $n_c^y = 1.4615$, $n_s^x = 1.457$, and $n_s^y = 1.4565$. The birefringence resulting from the stress effect of the elliptical inner cladding is $B = n_c^x - n_c^y = n_s^x - n_s^y = 5 \times 10^{-4}$. It should be noted that n_c^x, n_s^x, n_c^y, and n_s^y are the refractive indices corresponding to x-polarized light (major-axis direction) and y-polarized light (minor-axis direction) when the fiber is not spun.

Based on the boundary condition point-matching method[13,14], the propagation constant and leakage loss coefficient corresponding to the un-spun SMSP fiber are calculated. The related beatlength always increases with the wavelength and the beatlength at wavelength $\lambda = 1.55$ μm is $L_b = 3.093 \cong 3.1$ mm.

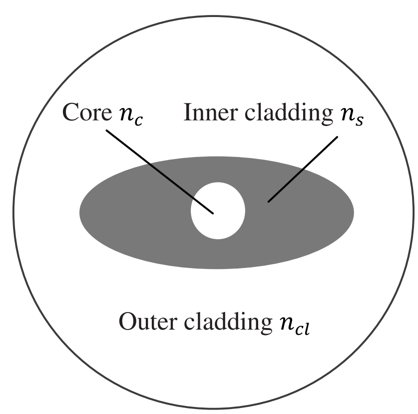

Fig. 6. Cross section of an SMSP fiber with a depressed elliptical inner cladding.

Characteristics of the spun SMSP with different spin rate and different wavelength are shown in Figs. 7–10, where the solid line, dotted line, dashed line, and dashed–dotted line represent spin pitch $\Lambda = L_b 5.8/1.3 = 13.8$ mm, $\Lambda = 5L_b = 15.5$ mm, $\Lambda = 4L_b = 12.4$ mm, and $\Lambda = 3L_b = 9.3$ mm, respectively; or the normalized spin rate at wavelength 1.55 μm is about 0.224, 0.2, 0.25, and 0.333, respectively. The fiber length is $L = 0.23$ m. As is shown in Figs. 7–10, the extinction ratio, the loss of the low-leakage eigenmode, and the loss ratio between the high- and low-leakage eigenmodes have a critical change at the x-polarized light cut-off point $\lambda_c^x = 1.558$ μm of the corresponding un-spun SMSP fiber, while the ellipticity increases gradually and only changes a little with a different wavelength. This is because the leakage loss of the x-polarized light increases more quickly than the y-polarized light when the wavelength is near the cut-off point of the x-polarized light in the un-spun SMSP fiber, so the loss of the low-leakage eigenmode in the spun SMSP fiber increases quickly when the wavelength increases from the cut-off point. This results in a critical decrease of the loss ratio between the high- and low-leakage eigenmodes and the extinction ratio decreases near the cut-off point also. From Figs. 7 and 8 it can be seen that the highest extinction ratio corresponding to the solid line is about 24.75 dB while

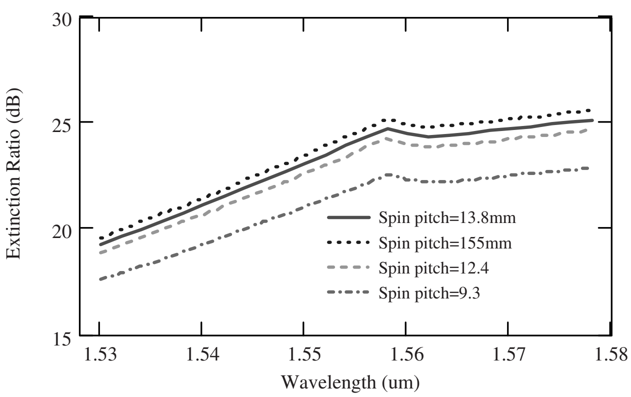

Fig. 7. Extinction ratio spectrum of a spun SMSP fiber with different spin pitches.

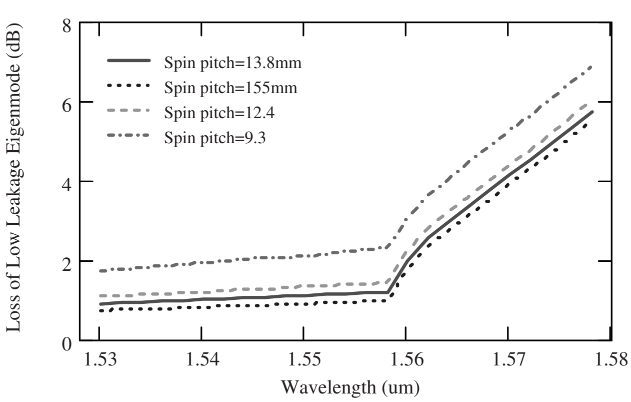

Fig. 8. Loss spectrum of the low-leakage eigenmode in a spun SMSP fiber with different spin pitches.

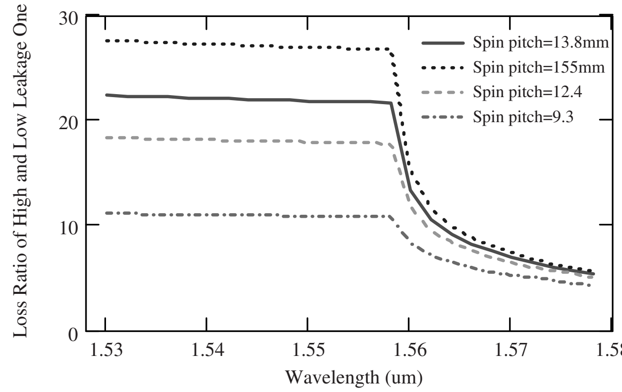

Fig. 9. Loss ratio between high- and low-leakage eigenmodes in a spun SMSP fiber with different spin pitches.

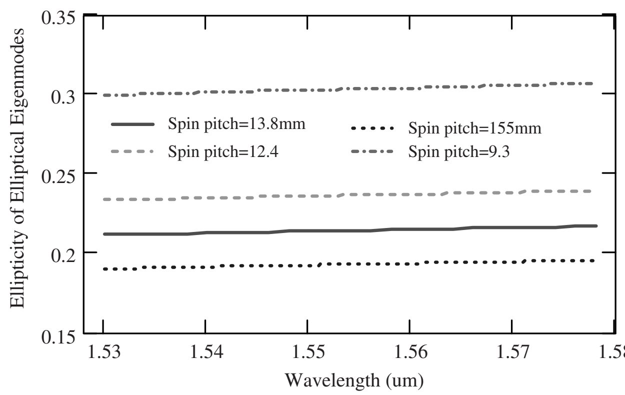

Fig. 10. Ellipticity of the elliptically polarized eigenmodes in a spun SMSP fiber with different spin pitches.

the loss of the low-leakage eigenmode is kept below 1.2 dB if the input light wavelength is within 1.558 μm. Increasing wavelength will lead to a higher leakage loss and the loss ratio between the high- and low-leakage eigenmodes will decrease radically. Consequently, the spun SMSP fiber should work within the cut-off wavelength region of the corresponding un-spun SMSP fiber.

The transmitting spectrum of the spun SMSP fiber is shown in Fig. 11. The loss of the low-leakage elliptically polarized eigenmode is smaller than 1.2 dB and the loss of the high-leakage elliptically polarized eigenmode is greater than 20 dB when the input light wavelength is in the region of 1.530–1.558 μm. This fiber can be used as a broad band elliptical polarizer or applied in current sensing.

From the previous theoretical and numerical results it is clear that the spun SMSP fiber that is named as spun SMSP can be used only within certain limits. To acquire high ellipticity or a circular polarized fiber the spin rate should be large enough or the spin pitch should be small enough (usually Λ should be smaller than one-fifth to one-tenth the un-spun fiber beatlength L_b). This will result in an enhanced averaging effect between the high-loss y-polarized light and guided low-loss x-polarized light. It will lead to enhanced loss of the low-leakage elliptically

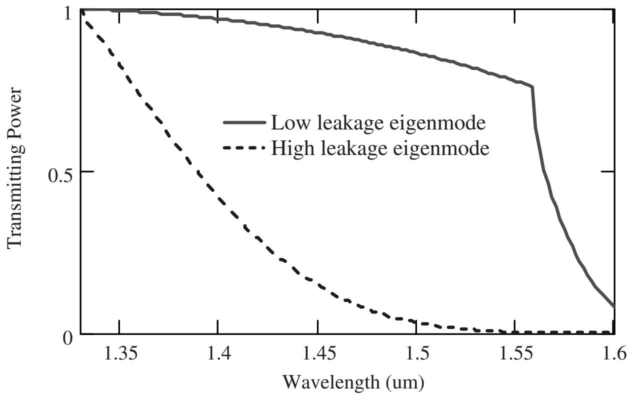

Fig. 11. Transmitting power in a spun SMSP fiber. Spin pitch, $\Lambda = 13.8$ mm; fiber length, $L = 0.23$ m; input power, normalized as one unit.

polarized eigenmode and decreased extinction ratio. In another aspect, if the spin rate is too small the ellipticity will be too small in that the ultra-low-spun SMSP fiber will be useless. For practical applications, the normalized spin rate $\frac{\tau}{\delta\beta} = \frac{L_b}{\Lambda}$ should be between 0.2 and 0.35. As a typical example, a spun SMSP fiber with moderate spin rate is shown. The spin effect on the local elliptically polarized eigenmodes and the transmission property with different wavelengths are analyzed. To keep the low-leakage elliptically polarized eigenmode transmiting properly, the input light wavelength should be within the cut-off wavelength region of the corresponding un-spun SMSP fiber, otherwise it will result in too large of a loss of the transmitted mode and too small of a loss ratio between the high- and low-leakage eigenmodes. This kind of fiber with specified un-spun beatlength $L_b = 3.1$ mm and spin pitch $\Lambda = 13.8$ mm can acquire single elliptical polarization on the wavelength from 1.530 to 1.558 μm. It can keep the loss of the low-leakage elliptically polarized eigenmode smaller than 1.2 dB while the loss of the high-leakage elliptically polarized eigenmode greater than 20 dB. This fiber may be used as an elliptical polarizer or applied in current sensing if it is fabricated appropriately.

References

1. A. J. Barlow, J. J. Ramskov-Hansen, and D. N. Payne, Appl. Opt. **20**, 2962 (1981).
2. A. J. Barlow, D. N. Payne, M. R. Hadley, and R. J. Mansfield, Electron. Lett. **17**, 725 (1981).
3. L. Li, J. R. Qian, and D. N. Payne, Electron. Lett. **22**, 1142 (1986).
4. R. I. Laming and D. N. Payne, J. Lightwave Technol. **7**, 2084 (1989).
5. R. Ulrich and A. Simon, Appl. Opt. **18**, 2241 (1979).
6. R. D. Birch, Electron. Lett. **23**, 50 (1987).
7. V. I. Kopp, V. M. Churikov, J. Singer, N. Chao, D. Neugroschl, and A. Z. Genack, Science **305**, 74 (2004).
8. G. Shvets, S. Trendafilov, V. I. Kopp, D. Neugroschl, and A. Z. Genack, J. Opt. A **11**, 1 (2009).
9. I. Victor, J. Lightwave Technol. **32**, 605 (2014).
10. I. Bassett, M. Bjarme, D. Chan, I. Clarke, J. Digweed, T. Ryan, A. Michie, and D. Wong, Proc. SPIE **3860**, 501 (1999).
11. H. C. Huang, *Microwave Approach to Highly Irregular Fiber Optics* (Wiley, 1998).
12. M. J. Messerly, J. R. Onstott, and R. C. Mikkelson, J. Lightwave Technol. **9**, 817 (1991).
13. M. N. Ji, Microwave Opt. Technol. Lett. **27**, 292 (2000).
14. M. N. Ji, Microwave Opt. Technol. Lett. **38**, 157 (2003).