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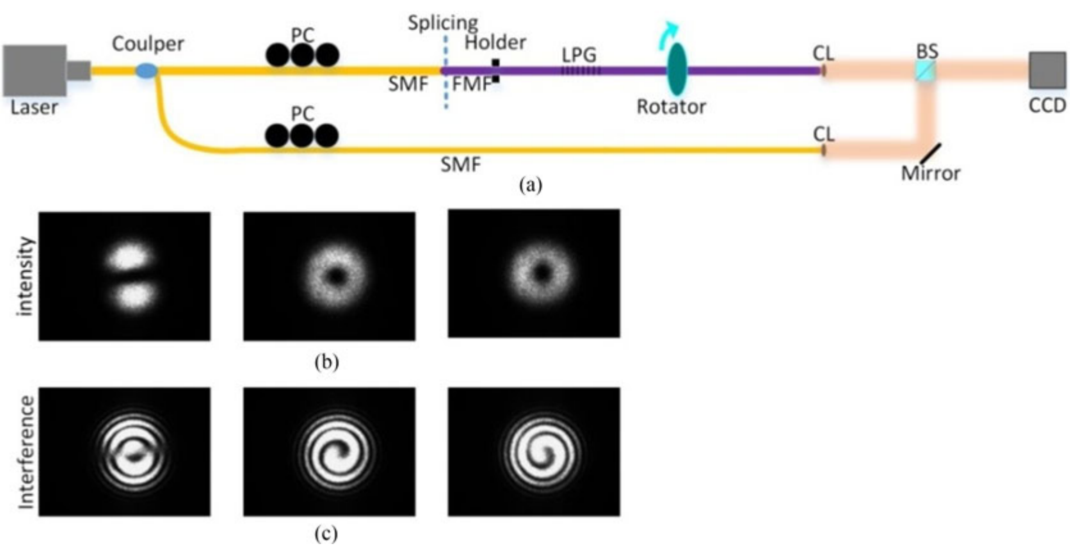

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Superposing Multiple LP Modes With Microphase Difference Distributed Along Fiber to Generate OAM Mode

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Abstract: We propose a new method to generate orbital angular momentum (OAM) mode by superposing multiple LP_{11} modes with microphase difference distributed along fiber propagation. This way, OAM mode can be generated by superposing a series of LP_{11} mode with phase difference much less than $\pi/2$, which is necessary for schemes using two degenerated LP_{11} mode superposition but is difficult to generate and hard to keep stable. We demonstrate this principle experimentally by utilizing few-mode fiber long period grating (FMF-LPG), in which a series of LP_{11} modes with microphase difference distribution can be generated by twisting FMF-LPG. This scheme provides a potential all-fiber, compact, and low-attenuation scheme to generate stable OAM modes.

Index Terms: Optical fiber communication, long period grating, few mode fiber.

1. Introduction

In recent years, orbital angular momentum (OAM) modes, have been characterized as having a helical phase wave-front of $\exp(\pm il\phi)$ and carrying OAM $l\hbar$ per photon, where l is a topological charge, ϕ is an azimuthal angle, and $\hbar$ is a reduced Plank constant [1]. These kinds of light beams with OAM have been investigated for a variety of applications including optical tweezers [2], quantum optics [3], nonlinear optics [4], and quantitative phase imaging [5]. Typically, most of the schemes for generating OAM modes require precise optical components, such as spiral phase plates, spatial light modulators, Q-plates or meta-materials-based phase plates [6]–[8]. However, these setups for generating OAM modes are costly and difficult to couple or control flexibly. It is well known that fibers have the ability to guide light flexibly according to objectives, which is especially important in bio-medical applications.

Recently, all-fiber based OAM components have been proposed and demonstrated. For example, a micro-bend grating effect on vortex fiber has been used to convert LP_{01} mode to OAM mode [9]. FMF-LPG is used as a mode converter to realize mode conversion from LP_{01} mode to LP_{11} mode first, and then, a metal flat slab is used to apply stress on FMF and generate the required phase difference between two degenerated LP_{11} modes [10] or using a few-mode fiber polarization controller (PC) [11] to realize the same function. Some schemes based on simulation are also proposed, such as helical grating [12] on air-core fiber, chiral fiber grating [13] on few mode fiber, a tunable micro-structure optical fiber [14], a multi-core fiber coupler [15], special ring fiber structures [16], helical core few mode fiber [17], and helical fiber Bragg gratings [18], all of which can be used as mode conversion from LP_{01} to OAM mode or between OAM modes.

The use of optical fibers as alternatives to free-space components still has room for improvements. The common experimental schemes based on fiber to generate OAM mode need to utilize the superposition of two degenerated LP_{11} mode with discrete phase difference of $\pi/2$ or $3\pi/2$. However, in many cases, it is hard to manipulate such large phase difference and hard to keep phase difference stable due to some limitations.

In this paper, we propose a new method to generate orbital angular momentum (OAM) modes by superposing multiple LP_{11} modes with micro phase difference distributed along the fiber. In this way, we can generate OAM mode by superposing a series of degenerated LP_{11} modes with phase difference much less than $\pi/2$, which is necessary for schemes using two degenerated LP_{11} mode superposition and difficult to generate in some cases. We demonstrate this scheme experimentally by utilizing few-mode fiber (FMF) long period grating (FMF-LPG), in which a series of LP_{11} modes with micro phase difference distributed along the FMF can be generated by twisting FMF-LPG. This provides a potential all-fiber, compact and low-attenuation scheme to generate stable OAM modes.

2. Principle of OAM Mode Generation

In this part, we will describe the principle and corresponding analysis on how to generate OAM modes, and we will compare the scheme superposing two degenerated LP_{11} modes with discrete phase difference and our scheme using multiple LP_{11} modes with equal micro phase difference.

It is already known that one pair of degenerated $HE_{n,m}$ modes with $\pi/2$ phase difference can be used to generate $OAM_{l,m}$ mode in an optical fiber. The relationship is given by [19]

$$OAM^{\pm}_{\pm l.m} = HE^{even}_{l+1,m} \pm jHE^{odd}_{l+1,m} \tag{1}$$

$$OAM^{\mp}_{\pm l.m} = HE^{even}_{l-1,m} \pm jHE^{odd}_{l-1,m}. \tag{2}$$

Under weak-guidance approximation conditions in optical fiber, HE_{21} mode is the mode base of LP_{11} modes. Thus, one pair of degenerated LP_{11} modes which satisfy the $\pi/2$ phase difference can also be used to generate $OAM_{\pm 1}$ modes in optical fiber [10]. The principle can be demonstrated by using COMSOL software. The field distributions of TE_{01}, HE^{odd}_{21}, HE^{even}_{21} and TM_{01} mode in *FMF* can be obtained by using FMF model in COMSOL software. Then, the field distribution of LP_{11} can be obtained by superposing TE_{01}, HE^{odd}_{21}, HE^{even}_{21}, and TM_{01} modes.

When we numerical analyze the data of two degenerate *LP* modes, we can personal set a $\pi/2$ phase difference before the superposition of the degenerate LP modes. The superposition result is shown in Fig. 2. Therefore, from the result of our numerical analysis, we can know that we get the OAM mode from the superposition, and our analysis is correct.

In Fig. 1, the dotted line is intended to show the intensity distribution of LP_{11a} mode in radius r_0. It can be found that the intensity distribution curve is very similar to cosine function distribution when normalizing the intensity distribution of LP_{11a}. Therefore, cosine function can be used to represent the intensity distribution of LP_{11} mode approximately as shown in (3), where $F_{11a}(r)$ is the intensity distribution of LP_{11a} mode in the radial direction

$$E_{11a} = \begin{cases} F_{11a}(r_0) * |\cos(\theta)| \exp(i * \pi) & (-\pi/2 \le \theta \le \pi/2) \\ F_{11a}(r_0) * |\cos(\theta)| \exp(i * 0) & (\pi/2 < \theta < 3\pi/2). \end{cases} \tag{3}$$

Simplifying (3), we can get

$$E_{11a} = F_{11a}(r_0) * \cos(\theta) \qquad (0 \le \theta \le 2\pi). \tag{4}$$

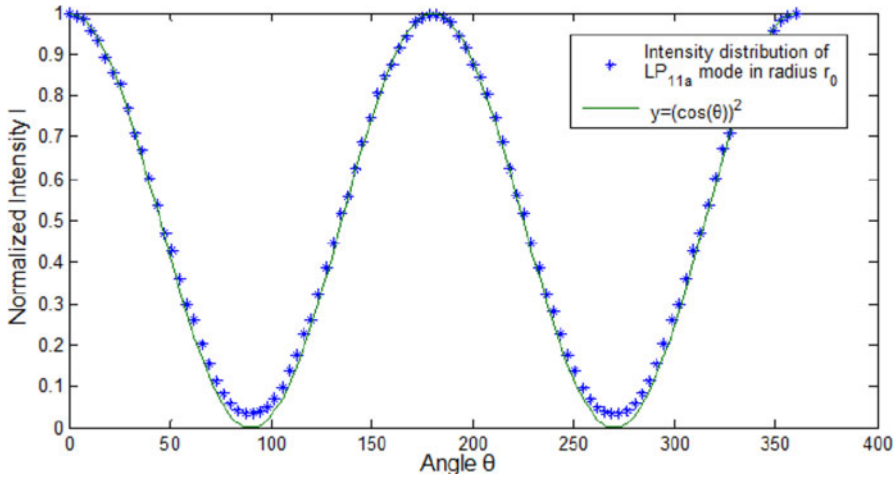

Fig. 1. Normalized intensity distribution of LP_{11} mode in radius r_0.

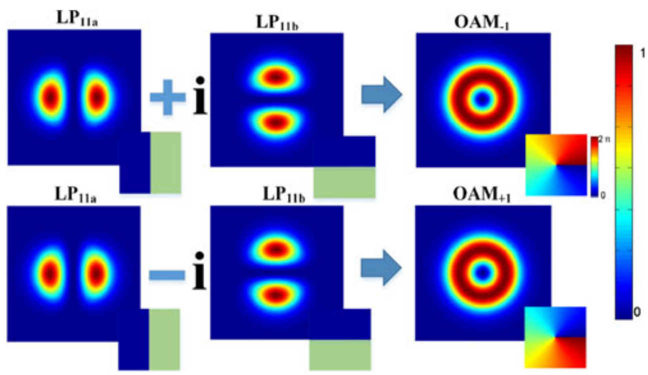

Fig. 2. Relationship between OAM $\pm$ 1 and LP_{11} modes.

Therefore, (4) is the final expression of electric field distribution of LP_{11a} mode. It can be used to calculate the superposed electric field distribution of two degenerated LP_{11} modes

$$\begin{aligned} E &= E_{11a} + i * E_{11b} \\ &= F_{11}(r_0) * (\cos(\theta) + i * \cos(\theta + \pi/2)) \\ &= F_{11}(r_0) * \exp(-1i * \theta). \end{aligned} \tag{5}$$

As we set $F_{11}(r) = F_{11a}(r) = F_{11b}(r)$, the electric field distribution of superposed LP_{11} modes could be represented as (5). It can be found that the phase distribution of superposed LP_{11} modes is clockwise spiral distribution, which denotes the phase distribution of OAM_{-1} mode. Consequently, the superposition of two degenerated LP_{11} modes which have $\pi/2$ phase difference is the OAM_{-1} mode. Similarly, OAM_{+1} mode can also be obtained when two degenerated LP_{11} modes superpose as having $3\pi/2$ phase difference. The generation of such $OAM_{\pm 1}$ modes are graphically illustrated in Fig. 2

However, in some cases, it is difficult to control the phase difference of two degenerated LP_{11} modes to exactly $\pi/2$ or $3\pi/2$ because of large refractive index manipulation. Therefore, it is important to identify ways to generate OAM mode by superposing LP_{11} modes with phase difference much less than $\pi/2$. In these cases, if we can generate a series of LP_{11} modes with distributed micro phase distribution, the accumulated phase difference can reach $\pi/2$ and OAM modes can be generated even though each of which cannot reach $\pi/2$. In principle, superposition of a series of LP_{11} modes

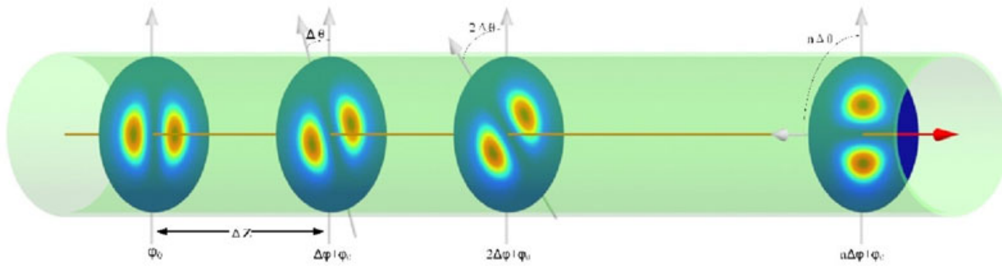

Fig. 3. Series of LP_{11} modes generated in each period of LPG with micro phase difference distributed along the fiber.

can be expressed as

$$E = \sum_{n=1}^{n=N} A_n * F_{11}(r) * \cos(\theta + n * \Delta\theta) * \exp(i * n * \Delta\varphi) \tag{6}$$

where $\Delta\theta$ and $\Delta\varphi$ represent different LP_{11} modes and phase difference between them, N is the number of the period of, and A_n represents the coupling coefficient of period. The phase difference $\Delta\varphi$ can be much less than $\pi/2$, which also means small phase or diffraction index change.

From the above analysis, different LP modes and corresponding distributed micro phase difference can be obtained by adjustin $\Delta\theta$ and $\Delta\varphi$, as shown in Fig. 3. When the superposed electric field distributions satisfied $E = A(r)\exp(\pm i\theta + \varphi_0)$, the $OAM_{\pm 1}$ mode electric field distribution can be obtained. The detailed electric field distribution of $OAM_{\pm 1}$ mode can be expressed as integral expression in the limiting case when N is large, i.e.,

$$E = F_{11}(r) \int_0^L A(z) * \cos(\theta + k_1 * z) * \exp(i * k_2 * z)\, dz \tag{7}$$

where $\Delta\theta = k_1 * \Delta z$, $\Delta\varphi = k_2 * \Delta z$, and L is the length of fiber where mode conversion happens, and $A(z)$ represents the weight of different LP_{11} modes along z direction. In order to get convenient calculation, we set $A(z)$ as a constant.

By simplifying (7), the real part and imaginary part of electric field distribution is given by

$$\begin{aligned} E_{real} &= A * F * F_{11}(r) * \left\{ \left(\frac{1}{2 * (k_1 - k_2)} \right) * [\sin(\theta + (k_1 - k_2) * L) - \sin(\theta)] \right. \\ &\quad \left. + \left(\frac{1}{2 * (k_1 - k_2)} \right) * [\sin(\theta + (k_1 - k_2) * L) - \sin(\theta)] \right\} \end{aligned} \tag{8}$$

$$\begin{aligned} E_{imag} &= A * F * F_{11}(r) * \left\{ \left(\frac{1}{2 * (k_1 - k_2)} \right) * [\cos(\theta + (k_1 - k_2) * L) - \cos(\theta)] \right. \\ &\quad \left. + \left(\frac{1}{2 * (k_1 - k_2)} \right) * [\cos(\theta + (k_1 - k_2) * L) - \cos(\theta)] \right\}. \end{aligned} \tag{9}$$

From the (8) and (9), the electric field distribution can be represented as

$$E = E_{real} + i * E_{imag}. \tag{10}$$

To make (10) satisfy $E = A(r)\exp(\pm i\theta + \varphi_0)$, it is easy to find that there are solutions under the following conditions:

$$\begin{cases} k_2 + k_1 = \dfrac{(2M+1)\pi}{L} \\ k_2 - k_1 = \dfrac{2N\pi}{L} \end{cases} \quad \text{or} \quad \begin{matrix} k_2 + k_1 = \dfrac{2M\pi}{L} \\ k_2 - k_1 = \dfrac{(2N+1)\pi}{L} \end{matrix} \tag{11}$$

where M and N are integers. Thus, it is feasible to generate OAM$_{\pm 1}$ mode by superposing a series of LP$_{11}$ modes with phase difference much less than $\pi/2$.

3. Generation of OAM in Few Mode Fiber

Based on above analysis, OAM$_{\pm 1}$ modes can be generated by superposing a series of LP$_{11}$ modes with micro phase difference. Therefore, a physical model is needed to generate a series of LP$_{11}$ modes that can match the required phase and intensity distribution.

As we all know, LPG can convert modes between LP01 and LP$_{11}$ modes under the phase matching condition $\beta_{01} - \beta_{11} = 2\pi/d$, where β_{01} and β_{11} are the propagation constants of LP01 and LP$_{11}$ modes, respectively, and d is the period of grating. Twisting the LPG will introducing phase matching condition deviating, which can be expressed as $\beta'_{01} - \beta'_{11} = 2\pi/d + \tau$, where $\beta'_{01,11} = \beta_{01,11} + \Delta\beta_{01,11}$ and $\beta'_{01,11}$ are the propagation constants of the twisted few mode fiber. Fiber twisting induces a change in propagation constant, which is determined by the azimuthal mode number via $\Delta\beta_{lm} = \tau p_{44}\varepsilon_{co}(l+1)/2$, where $p_{44} = (p_{11} - p_{12})/2$ and p_{11} and p_{12} are the photo-elastic constants, ε_{co} is the dielectric permittivity, regardless of the specific index step and optical wavelength [23], the additive item τ at the right-hand side is used to satisfy the equation. Substituting τ as $\Delta\varphi/d$, the phase matching condition represents as $\beta'_{01} - \beta'_{11} = (2\pi + \Delta\varphi)/d$, where $\Delta\varphi$ is the effective phase change induced by twisting. Besides, every two LP$_{11}$ modes generated by adjacent period of LPG will have an equal phase $\Delta\theta$ in angular direction. So through twisting FMF-LPG, a series of LP$_{11}$ modes are obtained with progressively changing phase difference, which means $\Delta\theta$ and $\Delta\varphi$ are arithmetic progression distributed along the FMF-LPG. Superposition of all these LP$_{11}$ modes along the fiber can obtain the final mode, which is an OAM mode.

Based on analysis of part 2, (6) can be simplified to

$$E = F_{11}(r) \int_0^L A(z) * \cos(\theta + \tau * z) * \exp(i * \Gamma * z)\, dz \tag{12}$$

where L is the total length of FMF-LPG, $L = N_0 * d$, d is period length of grating and N_0 is period number of grating; τ is twisting rate, $\tau = \theta_0/L_0$, θ_0 represents total twisting degrees of FMF and L_0 is the length of twisted FMF; Γ represents detuning factor, $\Gamma = \Delta\varphi/d$; $A(z)$ represents the weight of mode coupling along z direction, $A(z) = 2 * k * \sin(2 * k * z)$, k is a coupling constant, and $k = \pi/(2L)$.

To make (12) satisfy $E = A(r)\exp(\pm i\theta + \varphi_0)$, (13), show below, can be obtained from (11), where $\tau = k_1$ and $\Gamma = k_2$.

$$\begin{cases} \Gamma + \tau = \dfrac{(2M+1)\pi}{L} \\ \Gamma - \tau = \dfrac{2N\pi}{L} \end{cases} \quad \text{or} \quad \begin{cases} \Gamma + \tau = \dfrac{2M\pi}{L} \\ \Gamma - \tau = \dfrac{(2N+1)\pi}{L} \end{cases} \tag{13}$$

where M and N are integers. We set the initial conditions as

$$\begin{cases} \lambda_{input} = 1550 \text{ nm}, N_0 = 30 \\ L_0 = 180 \text{ mm}, \ d = 1.17 \text{ mm} \\ \quad 0 < \theta_0 < 1500^\circ. \end{cases} \tag{14}$$

According to (13) and (14), only one solution $\theta_0 = 1214^\circ$ is obtained. Under this condition, the twisting of FMF-LPG will generate perfect OAM mode. The relative power and phase distribution of LP$_{11}$are shown in Fig. 4(a) and the relative power and phase distribution of OAM are shown in Fig. 4(b). We can also find that phase difference in every period of FMF-LPG is only 0.0438π, which is easy to generate by manipulating the refractive index in fiber.

From the analysis above, it is clear that we can generate OAM$_{\pm 1}$ mode by superposing a series of LP$_{11}$ modes with distributed micro phase difference along FMF-LPG.

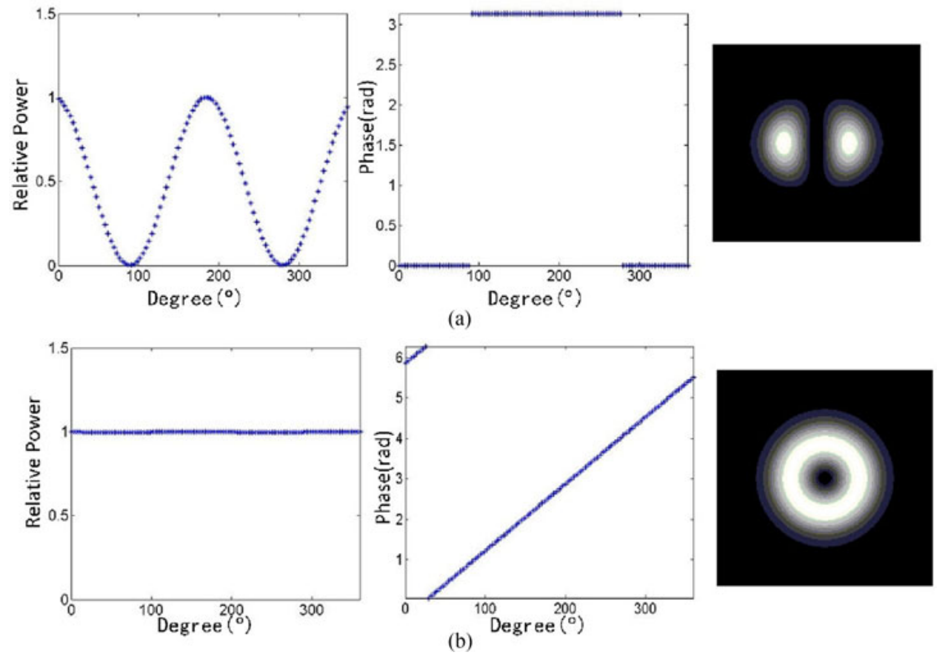

Fig. 4. (a) Relative power and phase distribution of LP_{11} mode as twisting degree is 0°. (b) Relative power and phase distribution of the numerical solution as twisting degree is 1214°.

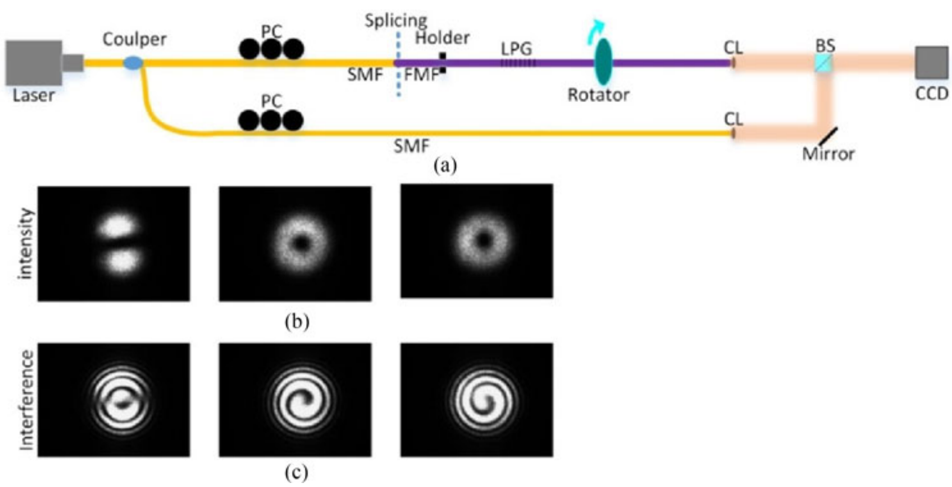

Fig. 5. (a) Experiment setup PC: polarization controller, LPG: long period grating, SMF: single mode fiber; FMF: few mode fiber; CL; collimator lens. (b) Experiment results of the mode after twisting the FLPG in different angles.

4. Experimental Results

The experimental setup used to generate OAM mode in FMF based on the proposed method is shown in Fig. 5(a). A DFB laser at 1550 nm is used as optical source with Gaussian beam and output power 13 dBm. A 3 dB optical coupler is used to divide light source into two arms with equal power. One arm is used as an experimental beam to generate OAM mode, the other is used as a reference beam to demodulate OAM mode. Then, two polarization controllers are used to control the polarization state of each arm. About one meter of FMF is spliced with single mode fiber. Long period grating (LPG) is written on FMF by using CO_2 laser [21]. The period of FMF-LPG is 1.17 mm, and the number of the period is 30. Then, a holder is used to fix FMF near the end of splicing point.

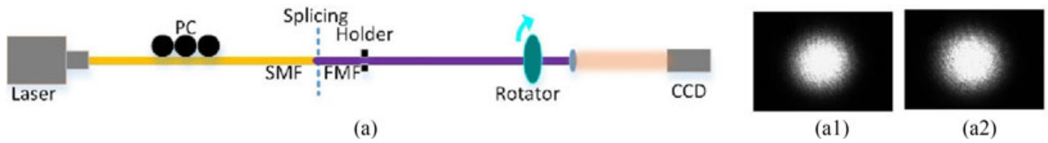

Fig. 6. (a) Experiment setup for proving the effectiveness of FMF-LPG based mode converter. (a1), (a2) the result of light beam after twisting FMF.

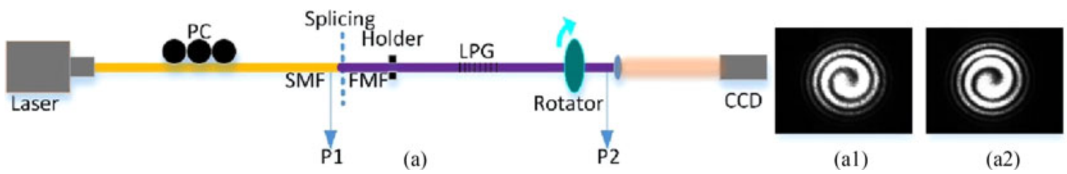

Fig. 7. (a) Experiment setup for demonstrating the stability of FMF-LPG based mode converter. (a1) Interference pattern of the converted OAM mode generated by twisting FMF-LPG. (a2) Interference pattern two days later.

The other end of FMF is fixed by a rotator. Length between the holder and rotator is 180 mm. FMF-LPG can be twisted with rotator. At the end of FMF, a collimator lens is used to generate free space beam. Then, a beam splitter (BS) is used to combine the output beam of FMF and reference SMF. A CCD camera is used to monitor the interference pattern of two light beams.

When twisting the FMF-LPG by adjusting the rotator, an input LP_{01} mode can be converted to an $OAM_{\pm 1}$ mode as shown in Fig. 5(b). By adjusting the rotating angle, the output beams can be adjusted as OAM_{+1} or OAM_{-1} mode. The counter clockwise spiral interference pattern for OAM_{+1} and the clockwise spiral interference pattern for OAM_{-1} are shown in Fig. 5(c). It can be clearly shown that the input LP_{01} mode is converted to $OAM_{\pm 1}$ mode when adjusting the rotator with appropriate angles while LP_{01} mode is converted to LP_{11} mode without rotation.

In order to confirm that OAM is generated depending on FMF-LPG, one experiment is also carried out to demonstrate that only twisting the FMF cannot convert LP_{01} mode to OAM mode. In Fig. 6(a), a single-mode fiber is spliced with FMF, a rotator is used to twist FMF and the output beam is monitored by a CCD camera. By adjusting the rotation angles, output beam still keep the LP_{01} mode. The beam profile in Fig. 6(a1) and (a2) are the experimental result when rotating FMF 90° and 180° respectively. It can be clearly indicated that just twisting FMF cannot realize mode conversion between LP_{01} and OAM modes.

Stability, purity, and power loss are important parameters for a mode converter. We also conducted corresponding experiments to measure such parameters. The experimental setup to demonstrate the stability of FMF-LPG based mode converter is shown in Fig. 7(a). A CCD camera is used to monitor the output OAM mode generated by twisting FMF-LPG for two days. Fig. 7(a1) is the recorded result at the beginning of the experiment, while Fig. 7(a2) is the recorded result two days later. By comparing the recorded experimental result, it is easy to find that the converted OAM mode by twisting FMF-LPG is stable.

The experimental setup to measure the power loss of FMF-LPG based mode converter is shown in Fig. 7(a). The power of mode is measured by a power meter in two positions of experimental system respectively. The power of input LP_{01} mode p1 and the power of converted OAM mode p2 are obtained from measuring modal power at two positions respectively. After measurements, p1 = 11.54 dBm and p2 = 10.88 dBm at two positions. Therefore, the power loss of mode converter can be calculated by

$$\Delta p = p1 - p2 = 0.66 \text{ dB} \tag{15}$$

where Δp denotes the power loss of mode converter. The power loss of mode conversion is 0.66 dB, which contains the power loss of fiber transmission and the splicing loss of SMF and FMF.

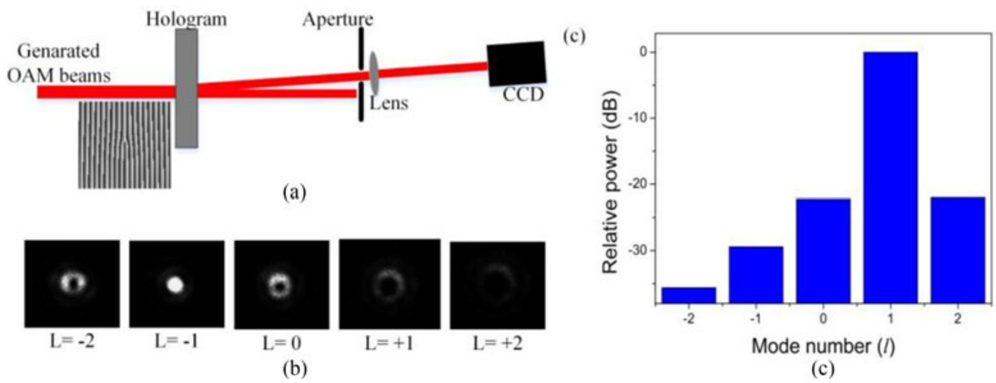

Fig. 8. (a) Setup for OAM mode purity measurements. (b) Beam profile recorded by CCD when a series of forked holograms (l = −2, l = −1, l = 0, l = +1, l = +2) is applied using a spatial light modulator. (c) Representative data set showing the high mode purity of the generated OAM beams, corresponding to a beam of primarily l = 1 OAM mode.

The experimental setup for OAM mode purity measurement is shown in Fig. 8. A hologram based mode content measurement scheme [22] is show in Fig. 8(a). The first-order diffraction of a beam from a forked grating of order l has an added helical phase $\exp(\pm il\theta)$. Thus, a forked hologram of order -l is used to convert the OAM mode with order l to LP_{01} mode. A series of forked holograms (l = −2, l = −1, l = 0, l = +1, l = +2) is applied using a spatial light modulator to monitor the generated OAM mode. The beam profile of the generated OAM mode after hologram is monitored by a CCD as shown in Fig. 8(b). The modal contribution of each OAM mode is measured by recording the power in the center of beam profile in Fourier plane. The relative power of each OAM mode among all generated OAM modes is calculated. From the representative data in Fig. 8(c), which corresponds to a beam of primarily l = 1 OAM mode, we can find that the measured OAM mode purity is more than 99%.

Compared to the existing OAM mode generating schemes [9]–[11] with fiber, the scheme proposed here could work with common few mode fiber. Then, if higher LP mode could be generated with LPFG, it is possible to generate high order OAM mode with this scheme. Additionally, this is a much compact and practical method because the LP mode generating and OAM mode generating are in the same section of fiber.

5. Conclusion

We propose a new method to generate orbital angular momentum (OAM) mode by superposing multiple LP_{11} modes with micro phase difference. In this way, we also demonstrate this scheme experimentally by utilizing FMF-LPG, in which a series of LP_{11} modes with micro phase difference distributed along the FMF can be generated by twisting FMF-LPG. The power loss and purity of this all fiber mode conversion component are 0.66 dB and 99%, respectively.

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