Demonstration of true-eigenmode propagation in few-mode fibers by selective LP mode excitation and near-field observation

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Abstract: We observed the near-field patterns of light output from few-mode fibers (FMFs) in which an LP mode was selectively excited. It was confirmed from the variation of the intensity profile with the wavelength that the true eigenmodes of a circular core fiber are guided in single-core step-index and graded-index FMFs. On the other hand, we discovered a new phenomenon that LP\textsubscript{11} modes propagate as eigenmodes oriented along a specific axis in 4-LP mode 12-core FMF. In addition, we confirmed that this phenomenon is not due to the elliptical deformation of the core by observing the NFP and calculating the eigenmodes in an elliptical core using elliptical cylindrical coordinates and the Mathieu function.

Keywords: few-mode fiber, multicore fiber, mode division multiplexing, LP mode, eigenmode

Classification: Optical systems

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1 Introduction

Single-mode and single-core optical fibers (SM-SCFs), which are widely used as a long-distance transmission medium, have succeeded in enormously increasing the capacity by wavelength-division multiplexing (WDM), polarization-division multiplexing, and multilevel modulation [1]. Although a large-capacity transmission of about 100 Tbit/s has been realized in experiments using SM-SCFs [2], communication traffic is expected to further increase in the future with the growth of advanced information devices and the Internet of Things (IoT). For this reason, it is becoming increasingly difficult to support user demand continuously by transmission using SM-SCFs. The physical factor limiting the input signal power is the nonlinear optical effect induced by the high optical signal power [3] and the fiber fuse, through which a destructive phenomenon propagates [4]. To overcome
these limitations and dramatically increase the transmission capacity of optical fibers, it is indispensable to realize next-generation optical signal transmission technology giving a new degree of freedom of space. Space-division multiplexing (SDM) is an attempt to realize the transmission of a number of optical signals by using spatially separated communication channels. There are many reports on SDM using multicore fibers (MCFs) [5] and mode multiplex transmission (MDM) using few-mode fibers (FMFs) [6] formed by increasing the core diameter of single-core fibers (SCFs).

In MDM using FMFs, the modes excited as the basis of transmission channels are linearly polarized (LP) modes [7] since linearly polarized light is used as a light source. Information has been successfully transmitted using multiple-input and multiple-output digital signal processing (MIMO-DSP) technology at the receiving end [8]. It has long been thought that the reason why MIMO-DSP is required is to compensate for the crosstalk caused by the roughness of the core-cladding interface and the macro- and microbending of the fibers. The exact reason, however, is that an LP mode is represented by a linear combination of multiple true eigenmodes [9], such as HE, EH, TE, and TM modes. Owing to the difference in the propagation constants between these true eigenmodes, the electromagnetic field distribution of the incident LP mode is not theoretically reproduced at the exit, except at a specific propagation distance, i.e., a multiple of the beat length of the interference between the true eigenmodes constituting the LP mode.

The relationship between LP modes and true eigenmodes in a cylindrical core optical fiber can be expressed in terms of a matrix formalism. We analyzed the electromagnetic field distribution along with the propagation when an LP mode is selectively launched into a fiber, and showed that the profile of the electromagnetic field of guided light launched as an LP mode at the input end evolves along with its propagation [10] owing to the difference in the propagation constants between the true eigenmodes [11]. As a result, mode discrimination and demultiplexing are difficult at the output end of an FMF and MIMO-DSP is essential. To overcome this problem, we previously proposed a method of realizing MDM transmission using true eigenmodes as transmission channels by constructing a multi/demultiplexer of true eigenmodes utilizing that of LP modes [10]. As long as the transmission distance is less than several kilometers so that the mode conversion or mode coupling is negligibly small [12], the MDM transmission using true eigenmode will be effective for a MIMO-free transmission. However, since perturbations such as macro- and microbending and the elliptical deformation of the core may occur in actual optical fibers, it is necessary to experimentally analyze how the eigenmodes propagate in an actual fiber and to study the effect of these perturbations. Therefore, in this study we experimentally observed the propagation of eigenmodes in FMFs by the selective excitation of the LP modes and observed the output near-field pattern (NFP) while changing the wavelength of the light source.

2 Theory of eigenmode propagation in few-mode fibers

In transmission experiments using FMFs, little attention has been paid to the difference in the propagation constant between LP modes, which are quasi-
degenerate, and MDM has so far been discussed using LP mode notation. However, an LP mode is represented by a linear combination of true eigenmodes, as expressed by the following equation [10]:

\[
\begin{bmatrix}
E(LP_{11-x}^{even}) \\
E(LP_{11-x}^{odd}) \\
E(LP_{11-y}^{even}) \\
E(LP_{11-y}^{odd})
\end{bmatrix}
= \frac{1}{\sqrt{2}} \begin{bmatrix}
1 & -1 & 0 & 0 \\
1 & 1 & 0 & 0 \\
0 & 0 & 1 & -1 \\
0 & 0 & 1 & 1
\end{bmatrix}
\begin{bmatrix}
E(TM_{01}) \\
E(HE_{21}^{even}) \\
E(HE_{21}^{odd}) \\
E(TE_{01})
\end{bmatrix}
\]

where the LP_{11-}^{even} mode means the x-polarized light of the LP_{11} even mode and the parity (odd or even) is determined by the symmetry of the electric field profile in the horizontal (x) direction. The 4 × 4 matrix on the right side of Eq. (1) can be separated into two 2 × 2 matrices, and the LP modes of the first and second rows (LP_{11-x}^{even} and LP_{11-y}^{odd}) correspond to the TMH group (TM_{01} and HE_{21}^{even}), while the LP modes of the third and fourth rows (LP_{11-x}^{odd} and LP_{11-y}^{even}) correspond to the TEH group (HE_{21}^{odd} and TE_{01}), respectively [11].

Since the light source used in the transmission generally emits linearly polarized light, the excited modes are always LP modes. However, even if an LP mode having a specific polarization direction and mode parity (even or odd) is launched into a fiber, the electromagnetic field distribution changes along with the propagation owing to the difference in the propagation constant between the eigenmodes. For example, when LP_{11-x}^{even} is launched into a fiber, a periodic transition between LP_{11-x}^{even} and LP_{11-y}^{odd} of the TMH group occurs as shown in Fig. 1 [10]. The beat length of the interference between the true eigenmodes constituting an LP mode ranges from several tens centimeter (TEH group) to several meters (TMH group) [10, 11]. In the intermediate state of the periodic evolution between two LP modes that belong to the same mode group, the electric field has a donut-shaped intensity distribution with locally different elliptical polarization in the cross section [10, 13, 14]. That is, it can no longer be expected that the input excited mode is reproduced at the output end of the FMF, and it is meaningless to demultiplex the output light using a mode demultiplexer for the LP mode.

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**Fig. 1.** Transition of electric field distribution along with the propagation of the LP_{11} mode belonging to the TMH group. The incident mode is assumed to be the x-polarized LP_{11} even mode [10].
3 Mode analysis using LP mode selective exciter and NFP observation system

It has been theoretically anticipated that interference between true eigenmodes will occur when an LP mode is launched at the input end and that the electromagnetic field has a donut-shaped intensity distribution and locally different elliptical polarization states as shown in Fig. 1. To verify this interference experimentally, we need to construct an observation system that distinguishes the intermediate states of the transition between two LP modes consisting of two eigenmodes belonging to the same mode group (TMH or TEH group). For this purpose, as shown in Fig. 2, it is appropriate to selectively excite an LP mode while changing the wavelength of the light source and observe the NFP of the light emitted from the FMF through a rotatable polarizer. This selective exciter can selectively excite any LP mode with an arbitrary polarization direction using a rotatable phase plate and a rotatable half-wave plate.

When the NFP is observed while rotating the polarizer at the exit and changing the wavelength, it can be determined whether the propagated light is formed by the interference between true eigenmodes or whether the LP$_{11}$ mode propagates as the eigenmode. If we observe the LP$_{11-\chi}^{\text{even}}$ or LP$_{11-\gamma}^{\text{odd}}$ mode using the measurement system shown in Fig. 2, the NFP should be observed most bright when the azimuth angle of the polarizer matches the polarization direction of the linearly polarized light. Furthermore, even if the output polarizer is rotated, the shape of the observed pattern does not change. The intensity of the NFP observed here is theoretically sinusoidal with respect to the azimuth angle of the polarizer. On the other hand, if a polarizer is inserted in the intermediate state (donut-shaped intensity distribution) in Fig. 1, the observed NFP changes with the azimuth angle of the polarizer, as shown in Fig. 3. Since the phase difference between the true eigenmodes constituting the output electromagnetic field depends on the wavelength, the NFP periodically transits between the LP$_{11-\chi}^{\text{even}}$ mode, the intermediate state, and LP$_{11-\gamma}^{\text{odd}}$ mode when the wavelength of the light source is changed, as shown in Fig. 1. On the other hand, we can determine whether an LP$_{11}$ mode propagates as the eigenmode at a specific angle at which an LP$_{11}$ mode pattern appears by rotating the phase plate in the measurement system shown in Fig. 2 without the polarizer.

Fig. 2. Experimental setup for observing modes propagating in fiber. It consists of a tunable laser, a selective LP mode exciter (rotatable half-wave plate and rotatable phase plate), and an NFP observation system (rotatable polarizer and infrared camera). The angle of polarizer was measured in clockwise from the negative x-axis.
4 Experimental results

Using the measurement system shown in Fig. 2, we observed the electromagnetic field profile of four FMFs. Table I shows the specifications of the FMFs used in our experiment. Two of them are the 2-LP mode (LP$_{01}$ and LP$_{11}$ modes) and single-core (SC) FMFs with a step index (SI) profile and a grated index (GI) profile in which the core exists only in the center. The remaining one is a 4-LP mode (LP$_{01}$, LP$_{11}$, LP$_{21}$, and LP$_{02}$ modes) and 12-core FMF [15]. The FM-MCF has a low-refractive-index trench in the region surrounding the core inside the cladding, and the core itself has a GI profile. The 12 cores are arranged in square [Fig. 5(b)].

![Fig. 3. Simulated NFP when observing the intermediate state (donut-shaped intensity distribution) in Fig. 1 through the rotatable polarizer in Fig. 2.](image)

| Fiber (Label) | SC-SI-FMF (Fiber A) | SC-GI-FMF (Fiber B) | 12-core GI-FMF [15] (Fiber C) |
|---------------|---------------------|---------------------|-------------------------------|
| Supported LP modes | 2-LP | 4-LP |  |
| Core diameter [µm] | 13.3 | 22.2 | 10.1 |
| Refractive index difference $\Delta$ [%] | 0.348 | 0.352 | 0.72 |
| Parameter $\alpha$ | ∞ (step) | ~2 | 2.0 |
| Core spacing [µm] | - (single core) | | 43.0–44.5 |
| Fiber length [m] | | | 100 |
| Curvature radius [cm] | | | 10 |

4.1 2-LP mode and single-core fibers

When the $x$-polarized LP$_{11}^{\text{even}}$ mode was incident on the SC-FMF at a certain angle, the observed NFP that passed through the output polarizer rotated by a certain angle was quenched at a certain wavelength and it turned out to be linearly polarized light, as shown in Fig. 4. However, when the wavelength of the light
source was slightly changed, an extinction angle did not appear, and a donut-shaped intensity distribution corresponding to the locally different elliptical polarization states was observed, as is seen in the column of $\lambda = 1547\, \text{nm}$ in Fig. 4(a) and in the column of $\lambda = 1549\, \text{nm}$ in Fig. 4(b). For example, Fig. 4(b) is in good agreement with the theoretical interference between the TEH group of true eigenmodes ($\text{TE}_{01}$ and $\text{HE}_{21}^{(odd)}$) [10]. Although the coordinate axis rotates in Fig. 4(b), if the direction of $+45^\circ$ is defined as the $x$-axis, the pattern at a wavelength of 1540 nm corresponds to the LP$_{11}^{-x}$ odd mode and the pattern at a wavelength of 1547 nm corresponds to the LP$_{11}^{-y}$ even mode, of which the polarization direction and parity are orthogonal to those of the LP$_{11}^{-x}$ odd mode. At a wavelength of 1549 nm, the intermediate state of the field evolution corresponding to Fig. 3 can be observed. When the LP$_{11}$ mode of the TMH group was launched into the FMF, the interference between true eigenmodes was also observed.

On the other hand, the interference between true eigenmodes can also be observed in Fig. 4(a), because the mode pattern and the direction of polarization at a wavelength of 1545 nm corresponds to the TMH group, which is the same mode group as the input mode, and those at a wavelength of 1547 nm corresponds to the intermediate state of the field evolution. However, the mode pattern and the direction of polarization at a wavelength of 1550 nm corresponds to the TEH group, which is orthogonal to the input mode. This seems to be caused by an imperfect selective excitation of the input mode resulting from the offset of incident beam at the input end of the FMF. Although this phenomenon can be explained using the transfer matrix between true eigenmodes at a connection point with offset [16], the detailed analysis is omitted due to the limitation of allowable number of pages.

To measure the core ellipticity of these FMFs, we used an optical microscope and observed the dark-field image of the cleaved fiber as shown in Fig. 5(a). The end facet was etched with buffered hydrofluoric acid (BHF) at room temperature for 5 min. Here, the ellipticity is defined by $e = (a - b)/a$, where $2a$ is the length of the major axis and $2b$ is the length of the minor axis. The ellipticity of the SI-FMF was evaluated to be 1.9%. However, in the GI-FMF, a clear step at the core-cladding boundary was not formed by etching, and thus, we could not observe the core shape.
4.2 4-LP mode and 12-core fiber

Next, we observed the NFPs of light output from an outer core of the 4-LP mode and 12-core GI-FMF using the same measurement setup as in Fig. 2. When the output polarizer was not inserted, the mode pattern of LP\(_{11}\) appeared when the phase plate was rotated by a certain angle, as shown in the first row of Fig. 6(a). The mode pattern did not change even when the half-wave plate was rotated while the azimuth angle of the phase plate was fixed. Next, we inserted the output polarizer and rotated the half-wave plate to launch the LP\(_{11-x}^\text{even}\) mode into the fiber. Then, even when the wavelength of the light source was changed, the mode pattern and the direction of polarization did not change as shown in Fig. 6(a). This pattern corresponds to the LP\(_{11-x}^\text{even}\) mode, and it was found that the incident LP\(_{11-x}^\text{even}\) mode propagated as the eigenmode or eigenstate of the core. On the other hand, when the incident LP\(_{11-x}^\text{even}\) mode was rotated by 45° in the azimuth direction, both the mode pattern and the polarization direction were rotated and varied with the change in the wavelength as shown in Fig. 6(b). It is concluded from these results that the principal axis of the mode parity exists only in the horizontal and vertical directions in this core. When the parity of the incident light did not match the direction of the principal axis specific to the core, interference between the orthogonal LP\(_{11}\) modes was observed. Even when the LP\(_{11}\) mode of the TEH group was excited and launched into the core, the direction of the principal axis was the same as that of the TMH group. We measured another outer core and an adjacent inner core and observed results are almost the same behavior as that of the first core, except for the direction of the principal axis of the LP\(_{11}\) mode.

![Image](https://example.com/image.png)

Fig. 5. Microscopic dark-field image of cross section of FMFs after etching with BHF. (a) SC-SI-FMF (Fiber A). (b) 4-LP mode 12-core GI-FMF (Fiber C). The marker is located at the lower left.

Next we observed the cross section of the FMF using the dark field of an optical microscope, as shown in Fig. 5(b). Since we found the marker in the lower left of Fig. 5(b) after the measurement in Fig. 6, we could not identify which cores were the measured cores. However, we measured three cores of the multicore FMF and it was found that these cores had their own principal axis of the LP\(_{11}\) modes that propagated in the FMF as the eigenmodes, as shown in Fig. 6(a). The ellipticity of the core was determined from the cross-sectional image of Fig. 5(b) and found to have an average value of 2.8%. Since this ellipticity is not significantly different from that of an SC-SI-FMF, it is considered that the existence of the principal axis of the LP\(_{11}\) modes is not due to the elliptical deformation of the core. Furthermore,
since the direction of the principal axis of the LP$_{11}$ modes did not coincide with that of the symmetry axis of the core arrangement, the origin of this phenomenon is difficult to directly attribute to stress. Here, there are three differences in structures from SC-FMFs. (i) The outer cores of 4-LP mode 12-core GI-FMF are susceptible to stress since they are not located at the fiber center, (ii) the $V$ value is larger than that of 2-LP mode FMFs, and (iii) a trench structure exists in the refractive index profile. However, we could not conclude the cause of the LP$_{11}$ mode becoming the eigenmode in this FMF. Anyway, although the intentional LP mode transmission has been realized using extremely elliptical deformed core fibers, we discovered a new phenomenon that the LP modes propagate as the eigenmodes in a few-mode multicore fiber with small ellipticity.

![Fig. 6.](image)

**Fig. 6.** NFPs observed from outer core of 4-LP mode and 12-core GI-FMF (Fiber C). (a) and (b) show the cases where the $x$-polarized LP$_{11}$ even mode is launched in the horizontal direction and rotated by 45°, respectively. It can be seen from (a) that the principal axis of the mode parity was located in the horizontal direction in this fiber core. In (b), mixing between the TMH and TEH mode groups occurred.

### 4.3 Evaluation of difference in equivalent indices

The difference in equivalent index (effective index) $n_{eq}$ ($= \beta/k_0$, where $\beta$ is the propagation constant of the mode and $k_0$ is that in vacuum) between LP$_{11}$ quasi-degenerate modes can be evaluated from the period of interference, which appears as the periodic variation of NFP when the direction of phase plate was rotated by 45 degrees from the principal axis. Here, we assumed the dependence of the refractive index of the material on the wavelength to be negligible. When the modes with $x$- and $y$-polarizations are excited at the same time, the same polarization state is obtained at a certain wavelength with the period $\Delta \lambda$, and the difference of equivalent refractive index is expressed by the following equation.

$$\Delta n = n_x - n_y = \frac{1}{L} \left( \frac{1}{\lambda} - \frac{1}{\lambda + \Delta \lambda} \right) \approx \frac{\lambda^2}{\Delta \lambda \cdot L}$$  \hspace{1cm} (2)

In this study, the length of the FMF was $L = 100$ m. First, we searched for the principal axis of another outer core different from that in Fig. 6 and found it to be oriented at an azimuth angle of 50° on the NFP. Then we launched an intermediate state between the LP$_{11}$ odd and LP$_{11}$ even modes (rotated 45° from the principal axis) into the core. The direction of the mode parity was determined by its principal axis. Since the polarization direction of the excited mode coincided with the principal axis specific to the core, the polarization direction of the output NFP
was expected to be constant regardless of the wavelength. However, although periodic rotation of the parity should theoretically occur in a range of 90°, corresponding to the angle between the odd and even modes, an oscillation of the direction of the LP_{11} mode occurred in a range a little less than 90° (approximately 70°–80°) in our experiment as shown in Fig. 7(a). Anyway we found that the difference in the equivalent index between the even and odd parities of the LP_{11} modes was almost on the order of 10^{-5} from the measured rotation cycle of the parity. The difference in the equivalent index of the x-polarized mode was slightly larger than that of the y-polarized mode.

We also launched LP_{11} odd and even modes with the polarization rotated by 45° from the principal axis. Fig. 7(b) shows the results when LP_{11} odd and even modes were launched, respectively. Even when the wavelength was changed, the direction of the mode pattern was not changed and only the direction of polarization was rotated. According to Fig. 7(b), when the LP_{11} odd mode was excited, the azimuthal angle at which the output light was quenched changed periodically with the wavelength, as shown in Fig. 8. Since this angle should change sinusoidally with respect to the wavelength, the difference in the equivalent refractive index

![Fig. 7. NFPs observed (a) when an LP_{11} mode is launched after rotating 45° from the principal axis with x-polarization, and (b) when the LP_{11} odd mode is launched by rotating the direction of polarization by 45° from the principal axis (Fiber C). Actual measurements were made with increment of 0.1 nm for (a) and 0.5 nm for (b). There are missing data due to a processing failure of the NFP observation software, but the periodic cycle can be observed. The angle of polarizer was measured in clockwise from the negative x-axis.](image1)

![Fig. 8. Plots of direction of minor axis of polarization state against wavelength obtained from data shown in Fig. 7(b) (Fiber C). The azimuth angles at which the output NFP is most quenched with respect to wavelength are plotted.](image2)
between the \(x\)- and \(y\)-polarized modes can be obtained by evaluating the period from a least-squares fit. As a result, the difference in the equivalent index between the \(x\)- and \(y\)-polarized LP modes was evaluated to be on the order of \(10^{-6}\) in the LP\(_{11}\) odd mode. In this way, we successfully experimentally evaluated the difference in the equivalent index between the LP\(_{11}\) modes, which propagate as eigenmodes in a 4-LP 12-core GI-FMF.

5 Analysis of deformation of true eigenmodes of elliptical deformed core

To evaluate the deformation of true eigenmodes in a circular core due to the elliptical deformation of the core, we analyzed the eigenmodes of an elliptical deformed core using elliptical cylindrical coordinates and the Mathieu function [17, 18, 19]. Although Adams reported a method of analyzing true eigenmodes propagating in an elliptical core in [17], only the fundamental mode was calculated. In addition, since this calculation considered only the first-order terms in the trigonometric expansion of the Mathieu function, the accuracy of the approximated solution was insufficient for a large value of ellipticity. Therefore, we first found the solution of the eigenvalue equation for the eigenmodes constituting the higher-order modes. By substituting it into the equation of the electromagnetic field

![Diagram](https://via.placeholder.com/150)

**Fig. 9.** Calculated distribution of electric field vector and intensity of (a) TE\(_{01}\) and (b) TM\(_{01}\) modes of elliptical deformed core obtained by analysis using elliptical cylindrical coordinates and the Mathieu function, and (c) power ratio of the \(x\)- and \(y\)-polarization components integrated in the core cross section.
distribution expressed by the elliptical cylindrical coordinate system and converting the equation into Cartesian coordinates, we obtained a vector diagram and the intensity distribution of the mode. Furthermore, we considered up to second-order terms in the trigonometric expansion of the Mathieu function and the Bessel function expansion of the modified Mathieu function to improve the accuracy of the calculation. Here we analyzed the TE\(_{01}\) and TM\(_{01}\) modes, in which the eigenvalue equation is simplified. According to the calculated results, the eigenfunction is hardly deformed and does not become the LP\(_{11}\) mode even when the core ellipticity is about 4% as shown in Figs. 9(a) and (b). The TE\(_{01}\) mode became LP\(_{11-x}^{\text{odd-like}}\) mode, and the TM\(_{01}\) mode changed into LP\(_{11-y}^{\text{odd-like}}\) mode owing to the elliptical deformation. Fig. 9(c) shows the calculated power ratios of the x- and y-polarization components. Since the core ellipticity of the FMFs measured in this study is less than 4% (the average is 2.0%), it is considered that the cause of the LP\(_{11}\) modes being the eigenstates of the FM-MCFs is not the elliptical deformation of the core.

6 Conclusion

We demonstrated the eigenmodes propagating in an FMF by selective LP mode excitation and output NFP observation through a polarizer while changing the wavelength of the light source. As a result, when launching a first-order LP mode into the FMF, interference between the eigenmodes was observed in 2-LP single-core FMFs. On the other hand, we discovered a new phenomenon that LP\(_{11}\) modes propagate as eigenmodes (eigenstates) in 4-LP mode 12-core GI-FMF. In addition, when observing the cross section of fibers with an optical microscope, all cores of the single-core and multicore FMFs had an ellipticity of 4% or less. However, the principal axes of the ellipse of the core and that of the LP\(_{11}\) modes in the multicore FMF did not always coincide. From the above experimental results, it is considered that the propagation of the LP\(_{11}\) modes as the eigenmodes in FM-MCF is for a reason other than the elliptical deformation of the fiber cores, for example, residual stress during the manufacture of the fibers, and the direction of such stress does not coincide with the axis of the core arrangement in FM-MCF.

On the other hand, the origin of the phenomenon that the LP\(_{11}\) mode becomes the eigenmode in multicore FMF has not been clearly specified. It is necessary to determine the type of mode that propagates when LP mode is launched into actual FMFs, on the basis of similar measurements using various FMFs with different parameters and strict numerical analysis assuming that various possible perturbations occur, which remains as a future subject of research.

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