LETTER

IEICE Electronics Express, Vol.10, No.21, 1–6

Technique for measuring mode power of two-mode fiber

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Abstract: We propose a simple method for measuring the mode power of two-mode fiber based on the bending method. The mode power ratio is determined with better than 1 dB accuracy by undertaking three power measurements with different numbers of fiber bends. We also evaluate the estimation error of the proposed method and the required resolution of the measurement.

Keywords: two-mode fiber, mode excitation ratio, bending method, fiber characterization, mode crosstalk

Classification: Fiber optics, Microwave photonics, Optical interconnection, Photonic signal processing, Photonic integration and systems

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1 Introduction

Recently, there has been increasing interest in few-mode fiber (FMF) as the next-generation fiber for achieving capacity beyond that of standard single-mode fiber [1, 2, 3]. FMF has better mode selectivity and can manage mode impairments more easily than approaches based on conventional multimode fiber (MMF). FMF transmission requires new research on few-mode devices that incorporate FMF. As their name indicates, few-mode devices support more than one mode, as the propagation mode. One of the fundamental properties of FMF is the power of each mode excited in it. When measuring

DOI: 10.1587/elex.10.20130740
Received September 22, 2013
Accepted October 10, 2013
Publicized October 18, 2013
Copyedited November 10, 2013

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the mode power launched into the two-mode fiber (TMF), the fundamental mode power can be approximated with the bending method [4]. The bending method utilizes the bending loss difference between the LP_{01} and LP_{11} modes. In a conventional measurement, the bending radius is chosen so that the LP_{11} mode is substantially attenuated while the bending loss of the LP_{01} mode is negligible, and two consecutive measurements are performed with and without fiber bending. The key to this method is the selection of the bending radius because both residual LP_{11} mode power and the attenuation of the LP_{01} mode power lead to estimation errors. When each mode power is measured, we can derive such characteristics as the mode excitation ratio, mode crosstalk, and mode dependent loss from the mode powers.

In this letter we propose a simple and precise technique for measuring the individual mode powers of TMF based on the bending method.

2 Principle of measurement

Fig. 1 is a schematic diagram of the technique for measuring the mode power of the LP_{01} mode (P_{01}) and LP_{11} mode (P_{11}) at a fiber output. As the fiber length of bending section L is short, we assume that the fiber loss and mode coupling between the modes at the bending section is negligibe. We also assume that there is no cladding mode at the fiber output.

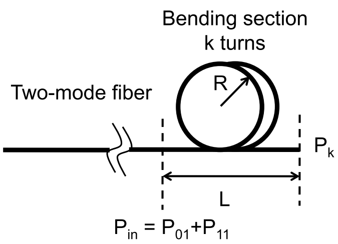

Fig. 1. Schematic diagram of technique for measuring mode power.

The method utilizes the bending loss difference between the LP_{01} and LP_{11} modes to evaluate P_{01} and P_{11}. Let the bending loss of the LP_{01} and LP_{11} modes be a [dB/turn], and b [dB/turn], respectively. There are four unknowns, namely P_{01}, P_{11}, a, and b, and these quantities are deduced from four power measurements under independent conditions. With the bending method, we can obtain an arbitrary number of equations by changing the number of times the fiber is bent. When the obtained output powers in $0, 1, 2 \ldots$, and N turns of the same bending radius R are given as $P_0, P_1, P_2 \ldots$, and P_N, we obtain the following equations

$$P_k = P_{01}10^{-ka/10} + P_{11}10^{-kb/10}, (k = 0, 1, 2, \ldots N). \quad (1)$$

By using the mode excitation ratio $X = P_{11}/P_{01}$

$$P_k = P_{01}(10^{-ka/10} + 10^{-kb/10}X), (k = 0, 1, 2, \ldots N), \quad (2)$$

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where $k = 0$ indicates no bending. It is convenient to use the linear losses $A = 10^{-a/10}$ and $B = 10^{-b/10}$ because we need to calculate the sum and the difference between the measured powers. The exact solutions of the P_{01} and P_{11} composed of more than 10 terms each. Instead, we deduce an approximate solution and evaluate its estimation error.

We approximate the bending loss of the LP_{01} mode to be zero, since it is much smaller than that of the LP_{11} mode in conventional optical fibers. When we employ this approximation, only three unknowns remain and so we retain three equations for $k = 0$, 1, and 2:

$$P_k = P_{01} + P_{11} * B^k, (k = 0, 1, 2). \tag{3}$$

These equations are solved to obtain

$$B = P_1 - P_2/P_0 - P_1, \tag{4}$$

$$P_{01} = P_0P_2 - P_1^2/P_0 - 2P_1 + P_2, \tag{5}$$

$$P_{11} = (P_0 - P_1)^2/P_0 - 2P_1 + P_2, \tag{6}$$

and the mode excitation ratio becomes

$$X = (P_0 - P_1)^2/(P_0P_2 - P_1^2). \tag{7}$$

This indicates that each mode power excited in TMF can be estimated by three power measurements for 0, 1, and 2 turns with a given bending radius R, if the power measurement is performed at sufficiently high resolution.

2.1 Estimation error

Now we evaluate the estimation error of Eq. (7). Hereafter, we denote the estimated values obtained by Eqs. (4) through (7) as $\hat{B}$, $\hat{P}_{01}$, $\hat{P}_{11}$, and $\hat{X}$. From Eq. (2) X and $\hat{B} - B$ are given by

$$X = (P_0A - P_1)/(P_1 - P_0B), \tag{8}$$

$$\hat{B} - B = \frac{(A - B)(1 - A)}{(1 - A) + (1 - B)X}. \tag{9}$$

Then B obeys the following equation

$$B = \frac{P_1 - P_2}{P_0 - P_1} - \frac{(A - B)(1 - A)}{(1 - A) + (1 - B)X}. \tag{10}$$

Substituting Eq. (10) for Eq. (8), we find

$$X = \frac{P_0A - P_1}{P_1 - P_0(\frac{P_1 - P_2}{P_0 - P_1} - \frac{(A-B)(1-A)}{(1-A)+(1-B)X})}, \tag{11}$$

then

$$\begin{aligned} \frac{1}{X} &= \frac{1}{\hat{X}}\frac{P_0 - P_1}{P_0A - P_1} + \frac{P_0(A - B)(1 - A)}{(P_0A - P_1)(1 - A + X - BX} \\ &= \frac{1}{\hat{X}}\frac{1 - A + X - BX}{(A - B)X} + \frac{(1 + X)(1 - A)}{X(1 - A + X - BX)}. \end{aligned} \tag{12}$$

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Finally, we determine the estimation error of the excitation ratio as

$$\hat{X}/X = (1 - A + X - BX)^2/X^2(A - B)^2. \tag{13}$$

This indicates that the estimation error deteriorates when A is close to B. Additionally, we introduce $\alpha = (1 - A)P_{01}$ and $\beta = (1 - B)P_{11}$, which is the power reduction of each mode caused by one turn, we obtain the simple relation

$$\hat{X}/X = (\alpha + \beta)^2/(\beta - \alpha X)^2. \tag{14}$$

Fig. 2 (a) shows the relationship between the LP_{01} and LP_{11} mode bending losses plotted as a function of $\hat{X}/X$ when $X = -10$ dB. Fig. 2 (b) shows the relationship plotted as a function of X when $\hat{X}/X = 0.1$ dB. The abscissa and ordinate show the bending losses of the LP_{11} mode and LP_{01} mode, respectively. The left hand side shows $\hat{X}/X = 1$, 0.1, and 0.01 dB plot for $X = -10$ dB, and the right hand side shows $\hat{X}/X = 0.1$ dB plots for $X = 0$ dB, -10 dB and -20 dB. When the bending radius is 10 mm, the estimated bending losses of the LP_{01} and LP_{11} modes of step index TMF with $V = 3.2$ and $\Delta = 0.4\%$ are 10^{-4} dB/turn and 1 dB/turn, respectively. Fig. 2 indicate that we can estimate the excitation ratio with better than 0.1 dB accuracy when it exceeds -20 dB.

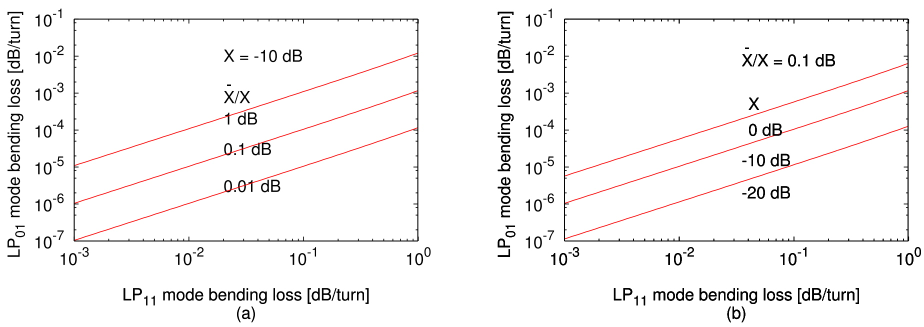

Fig. 2. Effect of bending loss of LP_{01} and LP_{11} modes on estimation error.

3 Alternative method for small excitation ratio

With a small excitation ratio of say -30 dB or less the power reduction of the LP_{11} mode induced by fiber bending is very small because the initial power of the LP_{11} mode is small. If the LP_{11} mode power can be reduced to a sufficiently low level, it does not affect power measurement by the bending method. When X is small and k is large, the second term in Eq. (2) can be neglected because the condition $A > B$ generally holds. With this assumption, we obtain the following relation

$$P_k \approx P_{01}A^k, \tag{15}$$

hence,

$$P_k/P_{k-1} \approx A. \tag{16}$$

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When Eqs. (15) and (16) are substituted into Eq. (2) of $k = 0$, we find

$$\hat{X} = \frac{P_0 P_k^{k-1}}{P_{k-1}^k} - 1. \tag{17}$$

Here again we evaluate the estimation error of Eq. (17). First we plot the required winding number k as a function of the bending loss of the LP_{01} and LP_{11} modes at a fixed estimation error as shown in Fig. 3. We find from the figure that the required winding number is almost independent of the bending loss of the LP_{01} mode when it is 10 dB smaller than the bending loss of the LP_{11} modes multiplied by the excitation ratio. So we try to derive the relationship between the required winding number k and the bending loss of the LP_{11} mode. The estimation error of Eq. (17) is written as

$$\frac{\hat{X}}{X} = \frac{\hat{P}_{11}/\hat{P}_{01}}{P_{11}/P_{01}} = \frac{\hat{P}_{11}}{P_{11}} \frac{P_{01}}{\hat{P}_{01}}. \tag{18}$$

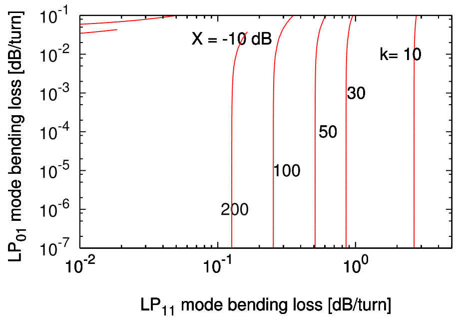

Fig. 3. Relationship between required winding number k and bending loss of LP_{01} and LP_{11} modes when estimation error is 0.1 dB.

Recall the relations $P_{01} = P_k/(A^k + B^k X)$ and $\hat{P}_{01} = P_k/A^k$, and after some manipulations, we find

$$\frac{\hat{X}}{X} \approx \frac{1 - B^k - k(1-B)B^{k-1}}{1 + B^k X}. \tag{19}$$

By comparing Figs. 3 and 4, we can say that Eq. (19) is a good approximation when $X \leq -10\,\text{dB}$. According to Eq. (19), $\hat{X}/X$ approaches 1 asymptotically as k increases, that is, an arbitrary high precision can be achieved by increasing the number of fiber turns.

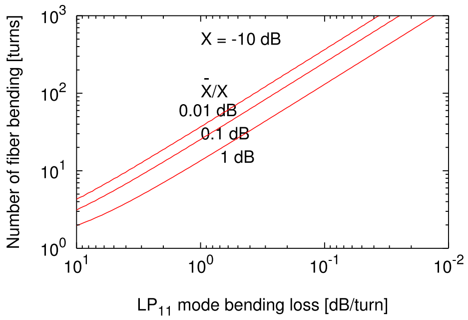

Fig. 4. Required winding number k vs LP_{11} mode loss.

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4 Required resolution of power meter

The proposed method measures a small power difference caused by fiber bending. The resolution of the power measurement must be better than this power difference. The measured powers P_0, P_1, and P_2 are nearly the same, and so it is natural to assume that all measured powers have the same relative uncertainty. We need three consecutive arithmetic operations, namely subtraction, multiplication, and division, to obtain the estimated excitation ratio $\hat{X}$ by using Eq. (7). According to the law of propagation of uncertainty, consecutive multiplication and division operations double the relative uncertainty, in other words, the relative uncertainty deteriorates by 3 dB. Subtraction enhances the absolute uncertainty by $\sqrt{2}$ times, or 1.5 dB, while the power difference is very small. When the excitation ratio is X dB and the bending loss of the LP_{11} mode is 1 dB, the power difference $(P_0 - P_1)/P_0$ is about $X - 6.9$ dB. In total, the relative uncertainty of $\hat{X}$ deteriorates by as much as $-X + 10.4$ dB compared with the relative uncertainty of the measured power. If we need to determine $\hat{X}/X$ at better than 1 dB, or a relative uncertainty of -6 dB, the power measurement should be performed with an uncertainty of better than about $X - 16.4$ dB. Roughly speaking, we must provide an additional two digits of resolution if we are to estimate an excitation ratio of better than 1 dB. Note that the subtraction operation cancels out the systematic uncertainty of the power meter when it is stable during the measurement time. Also note that increasing the bending loss by using a small bending radius or multiple turns will alleviate the resolution requirement.

With the alternate method given by Eq. (17), the relative uncertainty of the k-th power deteriorates approximately by k. That is, $k = 100$ causes a 20 dB penalty as regards accuracy.

5 Conclusion

We have proposed a simple technique for measuring the mode power of two-mode fiber based on the bending method. The mode powers, and hence the mode excitation ratio, cab be derived with only three power measurements with different numbers of fiber bends. We also proposed a method for evaluating a small excitation ratio. The measurement requires a large number of fiber bends but it is simple and high precision can be obtained.

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