QUANTITATIVE MODE ANALYSIS IN OPTICAL FIBERS

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ABSTRACT

An accurate method of determining the modal power distribution along optical fibers is described. Experimental results with the observation of launching conditions on an optical fiber demonstrate the accuracy of this method. Various factors having an important influence upon the accuracy are discussed, and also appropriate methods of minimizing the systematic errors are presented.

Introduction

In this paper, we present an analytical method for measuring the modal power distribution at the output end of an optical fiber. Instead of the mode selection technique proposed in [1], we make an interferometric recording of the far-field amplitude distribution at the output of a fiber and analyze this recording by computer. The modal power distribution at the output end is intimately related, of course, to launching cnditions excited by an input laser beam, and then a technique for measuring launching condituions characterized dominantly by three parametersis also presented. The results of the mode analysis are discussed with reference to the measured launching parameters. In addition, various factors having an important influence upon the accuracy are also discussed with methods of minimizing the systematic errors.

Experimental setup and Theory

Experimental setup and arrangement

Fig.1 shows the experimental setup which has an improved stability more than for the interferometer of [2]. A SELFOC fiber was used for a test, and its maximumrefractive index is 1.54, the quasi-core diameter is 35μm and has a length of 1 m. The several kinds of interference patterns at λ=.633μm are observed on both planes P_1 and P_2. Each of them is recorded on the image strage tube through a TV camera and then sampled data are aquired into a computer for the followung processing.

Theory of mode analysis

For the mode analysis, it is assumed that the field E_0 on the output end of a SELFOC fiber may be given, in the scalar approximations, by the superposition of TEM eigen mode functions e_{mn} themselves. The field E_f in the Fraunhofer region is then expressed in terms of the Fourier transform of E_0 as examined in [1]. Thus, if we can measure experimentally the complex amplitude distribution of E_f, the modal amplitudes A_{mn}, which are defined in the expression of

$$E_0=\Sigma\Sigma A_{mn}\, e_{mn}\ ,$$

may be obtained approximately by introducing the orthogonality condition of e_{mn} into the inverse Fourier transform of E_f. Of course, more rigorous treatments should be considered by considering the hybrid nature of eigen mode and these have been discussed in [2].

Measurement technique of complex amplitude distribution

To obtain E_f which may be expressed as $|E_f|\cdot \exp(j\Theta_f)$, the Mach-Zehnder interferometer-like arrangement in the right-hand side of Fig.1 is used, where the lens L_2 serves to collimate the radiation field. After splitting the beam at BS_2, one of these is transmitted directly and yields E_f itself across the plane P_2, while the other in the lower arm of the interferometer generates a homogeneous plane wave by means of a DC spatial filter and is used as a reference wave R. These are recombined at BS_2' to yield the desired interference pattern on the plane P_2. In addition, the E_f is also interfered with another reference wave R', of which phase is advanced by $\pi/2$ with respect to R.

Consequently, the recorded patterns, i.e., $|E_f+R|^2$, $|E_f+R'|^2$, $|E_f|^2$, $|R|^2$ and $|R'|^2$, are then sampled in a sufficiently close separation and analyzed to obtain both the amplitude $|E_f|$ and phase Θ_f of E_f.

Measurement technique of launching condition

The Mach-Zehnder interferometer-like arrangement in the left-hand side of Fig.1 is used for the measurement of launching parameters which may be represented by the physical parameters such as the tilt angles γ , δ and the axial mismatch a of an input beam as denoted in Fig.2. Here we restrict our interest to the input beam with given minimum spot size ω_0.

To measure these parameters, the output beam from a laser is split at BS_1 and one of these excites a fiber through the launching lens L_1 in the same fashion as shown in Fig.2. The reflection at the input plane produces the far-field distribution associated with the launching condition across the plane P_1, while the other, after generated a homogeneous plane wave by means of a DC spatial filter, reaches to P_1 as a reference wave. These waves interfere on the plane P_1 and produce an off-axis Airy-like pattern. The center coordinates (x_{ic} , y_{ic}) of it are related to the tilt angles γ , δ , while the axial mismatch a is derived from the difference of radii of successive maxima in that pattern. In addition, a microscope-like arrangement enclosed by the dashed line in Fig.1 is used to observe directly the intensity distribution of launching beam and its center coordinates (x_c , y_c) on the input plane of a fiber.

Experiments

To examine the relations between the launching condition and the modal power distribution, several experiments have been performed by means of the present methods. A few results are summarized in Tables (1) ~ (3). Fig.3 shows examples of the photographic recordings of the field intensity distributions and the interference fringes observed in the experiment for Table (2). Although all of these results are obtained for the input beam having ω_0=5.2μm which coincides with the eigen spot size of a SELFOC fiber, our results suggest that the coupling of input beam into the higher order propagation modes is less affected by the incomplete launching having both finite tilt angles and axial mismatch rather than that having the off-axial center of

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input beam onthe input plane.

Discussions

To obtain the accurate results in the mode analysis, the special attention should be paid, at least, to the following three, i.e., (1) the allowable separation Λ between samples for the recorded patterns, (2) the recovery of original data for E_f from the sampled data E_f' and (3) the minimum radius R_m for the lens L_2 to give no influences on the radiated eigen mode fields.

For the first problem, it may be roughly assumed that the output field E_0 is confined in and near the quasi-core region for well-guided modes, and thus the field E_f will be regarded as a spatially band-limited function. Then the Nyquist condition defines the sufficient separation Λ as $\lambda f/2r_0$, where f is the focal length of L_2 and r_0 is the quasi-core radius. In our case, this separation becomes about 1.26 mm, but the electronic sampler has been operated with .9 mm spacing in the experiments.

In the second problem, the sampled data E_f' are convolved, in our case, with the window function of electronic sampler. Then the desired original data E_f may be obtained by applying the deconvolution technique successfully developed in [3],[4].

Finally, the minimum radius R_m for lens L_2 may be derived from the N.A. of a fiber. Supposing the radiation field for the highest order mode in a fiber to be concentrated in a cone with with the apex angle Θ_m, it is obvious that the relation, $R_m \simeq f\Theta_m$, should be held. In our case, R_m is given by 15 mm, but the lens with a radius of 25 mm is used in experiments.

Furthermore, there are some residual factors which influence the systematic errors. These are, for examles, the reduced visivility in the interference patterns produced by the spatial coherency of a laser and the misalignment of interferometers. These have something in common with the ordinary laser interferometers and the counterplans considered in those fields are, of course, effective.

We are currently working to improve the arrangement for applying this techniques to a long fiber and to discuss the accuracy of the techniques in more details.

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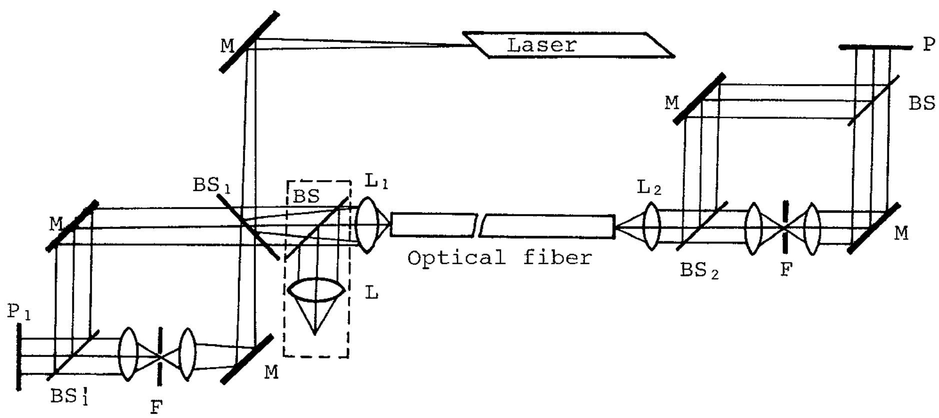

Fig.1. Experimental setup for measuring the launching parameters and for the mode analysis.

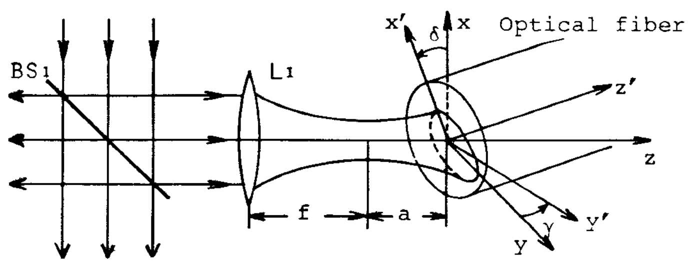

Fig.2. Definition of launching parameters,i.e.,tilt angles δ , γ and axial mismatch a.

Table. Typical results obtained in the mode analysis.
(δ , γ in degrees and a, x_c, y_c in millimeters)

(1)

$\delta=-4.01$, $\gamma=1.92$
$a=0$, $x_c=-0.03$
$y_c=0.02$

Mode	|Amn|
TEM-02	1.00
-20	0.90
-10	0.71
-30	0.50
-22	0.49
-07	0.44
-00	0.44
-03	0.43
-06	0.42
-11	0.41
-04	0.41
-01	0.36
-15	0.36
-21	0.36
-13	0.34

(2)

$\delta=4.32$, $\gamma=-2.07$
$a=-0.12$, $x_c=-0.02$
$y_c=-0.01$

Mode	|Amn|
TEM-10	1.00
-00	0.72
-14	0.60
-11	0.56
-04	0.43
-03	0.39
-13	0.37
-12	0.32
-30	0.30
-15	0.29
-06	0.23
-07	0.23
-22	0.22
-20	0.21
-23	0.21

(3)

$\delta=5.12$, $\gamma=-2.14$
$a=-0.13$, $x_c=-0.02$
$y_c=-0.01$

Mode	|Amn|
TEM-12	1.00
-10	0.91
-11	0.74
-06	0.70
-09	0.67
-04	0.61
-03	0.51
-01	0.49
-30	0.48
-21	0.44
-20	0.38
-13	0.32
-24	0.32
-00	0.30
-15	0.29

(a) (b) (c)

Fig.3. Examples of the photographic recordings.
(a) Intensity distribution of launching beam on the input plane, (b) Interference pattern on P_1, and (c) Near-field pattern on the output plane of a fiber.