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Twisting effect on LP_{11} mode in optical fibers

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ABSTRACT

We study the light propagating in a dual mode optical fiber with torsional mechanical stress. By twisting the fiber and distinguishing the LP_{01} and LP_{11} modes using wavelength-scanning spatially and spectrally resolved imaging technique (S2 Imaging), we show the twist induced mode variation of the intensity distribution and phase pattern of the fiber. The linear and nonlinear variation of the mode rotation with the physical twist of the fiber is observed and discussed. The experimentally obtained LP_{11} mode intensity fluctuation of the fiber is also presented. The mechanism provides a way to control the fiber mode pattern, which may find potential use in long-range robust transmission of mode division multiplexing.

1. Introduction

With the Internet traffic growing exponentially every year, capacity limit of the standard single-mode fiber (SMF) will be exceeded inevitably even under high spectrum efficiency. Space division multiplexing (SDM) [1] and mode division multiplexing (MDM) [2,3] have been proposed as two available solutions to the problem of capacity saturation of the SMF and to increase the transmission capacity of the optical transmission systems.

As one of the promising approach, multimode fibers (MMF) based MDM [3] is firstly implemented by S. Berdague and P. Facq in 1982 [4]. While the technique has been proposed for years, steps have to be taken as the technique aims towards practical application. For an optical transmission system based on mode division multiplexing technique [2], mode crosstalk is one of the key factors for its practical performance. On the one hand, mode crosstalk is imposed by mode coupling induced by fiber imperfections, fiber bending, and twisting [5]. Common sources of perturbation has been carefully studied as to get a better understanding of the mode coupling mechanism [6]. On the other hand, misalignment of the mode orientation of the non-circular symmetric modes between the mode division demultiplexer and the mode division multiplexer causes mode crosstalk during the mode division de-multiplexing process as well [7]. Mode rotators [8,9] have been proposed to compensate the spatial orientation induced during the fiber mode propagation.

In order to reach a relatively low mode crosstalk, differently designed mode rotators are required for one mode division multiplexing system to align the fiber mode orientations under various perturbation conditions. The use of these mode rotators indeed help lower the mode crosstalk, while they increases the cost, complexity and the insertion loss [9] of the system as well.

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In this paper, we carefully investigate the twist effect on optical fiber using spatially and spectrally resolved imaging technique (S2 Imaging) [10], which is a versatile tool for modal content characterization. Twist induced mode variation of the intensity distribution and phase pattern is observed and discussed using optic-elastic effect. Intensity fluctuation of the LP_{11} mode is also observed. The mechanism provides a way to rotate the fiber mode and at the meantime causes low power exchange between the different mode orders, which may help eschew the use of mode rotator and find potential in long-range robust transmission of mode division multiplexing.

2. Spatially and spectrally resolved imaging technique

Spatially and spectrally resolved imaging technique (S^2 *Imaging*) was first proposed by Nicholson et al. [10] and was demonstrated to be a good way to characterize the mode content in optical fiber. The method has been used to characterize hollow-core photonic fiber [11], fiber amplifiers [12], polarization maintaining fibers [13], and is also capable of real-time analysis [14]. For the sake of completeness, we briefly review here some of the principles of the S^2 *Imaging* [10].The idea of S^2 *Imaging* is to achieve the amplitude and phase of individual fiber mode with different group delay by spatially resolving the spectral interference between the HOMs and the LP_{01} modes propagating in the fiber under test (FUT). The analyze is based on the fact that the Fourier transform of the power spectrum, derived from experimental collected three dimensional set of data in (x, y, λ), is the group delay spectrum.

Two propagating field (the fundamental and one of the higher order modes) in an optical fiber are assumed to be $E_1(x, y, \omega)$ and $E_2(x, y, \omega)$ which are related in the following way

$$E_2(x, y, \omega) = \alpha(x, y)E_1(x, y, \omega) \tag{1}$$

where $\alpha(x, y)$ is assumed to be constant at a given point and independent of wavelength. The interference between two fields causing the spectral intensity pattern is then described as

$$I(x, y, \omega) = I_1(x, y, \omega)[1 + \alpha^2(x, y) + 2\alpha(x, y)\cos(\omega\Delta\tau_b)] \tag{2}$$

where τ_b, assumed to be independent of frequency, is the period of the beating frequency between the two modes caused by their relative group delay difference. Fourier transform of I_1 and of the interference spectral intensity is then

$$F_1(x, y, \tau) = \mathcal{F}\{I_1(x, y, \omega)\} \tag{3}$$

$$F(x, y, \tau) = [1 + \alpha^2(x, y)][F_1(x, y, \tau - \tau_b) + F_1(x, y, \tau + \tau_b)] \tag{4}$$

Assuming that the width of $F_1(x, y, \tau)$ is small compared to τ_b, ratio $f(x, y)$ between the amplitude of the Fourier transform of the spectral intensity at the group delay difference of τ_b and 0 can be mathematically expressed as

$$f(x, y) = \frac{F(x, y, \tau = \tau_b)}{F(x, y, \tau = 0)} = \frac{\alpha(x, y)}{1 + \alpha^2(x, y)} \tag{5}$$

Knowing the relation between the ratio of two mode and also their total intensity, the intensity of each mode is then given by

$$I_1(x, y) = I_T(x, y)\frac{1}{1 + \alpha^2(x, y)} \tag{6}$$

and

$$I_2(x, y) = I_T(x, y)\frac{\alpha^2(x, y)}{1 + \alpha^2(x, y)} \tag{7}$$

where $I_T(x, y) = I_1(x, y) + I_2(x, y)$ is the total intensity of a given point, which can be obtained by integrating the experimentally collected three dimensional dataset(x, y, λ) at a certain (x, y) point.

From the experimental point of view, there are two ways of achieving the three dimensional dataset. One is the setup used in the original proposed S^2 method, where a broadband source was used as input source and a single mode fiber probe, which was coupled to an optical spectrum analyzer (OSA) and placed on an automated translation stage, was used to obtain the output power. By scanning the end-face of the tested fiber with the probe, the spectrally resolved image could be realized thus obtaining the three dimensional set of data in (x, y, λ).

An alternate way, introduced by Nguyen et al. to obtain the same three dimensional set of data through wavelength sweeping instead of spatial scanning is used in our experiments and thoroughly described as follow. The experimental setup of S^2 *Imaging* measurement is shown in Fig. 1. A tunable laser source (TLS) was set to sweep mode and a trigger was generated and sent to the CCD camera each time a step finished, allowing the CCD camera to capture interference patterns accordingly. The TLS output SMF is spliced to the fiber under test (FUT) with an offset of about 2 μm as depicted in the inset of Fig. 1, so that the LP_{01} mode is dominant while HOM is also excited with its peak amplitude in the Fourier transformation of the spectrum sufficiently low compared to the fundamental mode, which is an important condition under which S2 method is valid. A pair of lenses was used to provide magnification of the output beam at the image plane. A polarized controller (PC) ensures that the linearly polarized LP_{01x} and LP_{01y} mode propagate separately through the single mode fiber (SMF). A