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Improvement of refractive index profiling of a small-core single-mode fiber under partially coherent light excitation

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ABSTRACT

The refractive index profile of a non-bending small-core single-mode fiber was first reconstructed from the measured guided mode intensity profile and its spatial derivatives. By combining a rotating diffuser with a coherent laser source, the resulting partially coherent light source overcomes the speckles on the guided mode image of a straight fiber, and the corresponding refractive index profile was successfully reconstructed. Furthermore, guided mode images of a bent fiber with a fiber coil at midway were also measured under different coherency light excitations for comparison. The slight asymmetry of the reconstructed index profile of a bent fiber measured under coherent light excitation was greatly improved when measured under partially coherent light excitation. The generated additional leaky modes propagating partly in both core and cladding induced by the effects of the fundamental core mode deformation at the intermediate fiber bending structure and the mode transition at the bent-to-straight fiber section were averaged out with a low coherence transformed light source.

1. Introduction

Laser has been known to be a highly coherent light source. When launching laser light into a straight fiber, speckles can be seen as small light spots that distributed randomly on the optical pattern of the fiber endface [1]. This is due to the interferences between higher-order modes under highly coherent light excitation. For a multimode fiber, speckles were observed in both core and cladding regions, where higher-order core modes and cladding modes exist. For the case of a single-mode fiber, the speckles were only in the cladding region, where higher-order cladding modes exist.

Single-mode fibers have the advantages of high data transmission rate and zero modal dispersion over multimode fibers in optical communication, and are thus widely used in signal modulation and dense wavelength division multiplexing (DWDM) [2]. The knowledge of refractive index profiles of a single-mode fiber is crucial in predicting its optical properties, such as mode field profiles, cutoff wavelength for single-mode operation, chromatic dispersion characteristics, and so on [3]. Other nonlinear optical properties also relate to the refractive index profiles, such as the intensity-dependent refractive index of fiber grating optical switching devices [4,5]. The refractive index profiling of single-mode fibers has been demonstrated for several decades, such as interferometry [6,7], reflective [8], refracted [9,10], or transmitted near-field methods [11]. Among these, the transmitted near-field (TNF) is a non-destructive method to characterize a small-core single-mode fiber, since it reconstructs the refractive index profile from the measured guided mode image. However, field-smoothing or spatial-filtering techniques are required to obtain the second-order derivate of the measured field with numerical process [11,12], which may cause distortion of the exact mode and index profiles. Previous work has shown to directly reconstruct fiber index profile by simultaneously measuring the guiding mode intensity and its spatial derivatives with a modified end-fire coupling method [13,14]. The issues of noises amplified by the numerical differentiation and profile-distortion by field-smoothing procedure are thus solved. Furthermore, since the guiding mode images and its spatial derivatives are obtained from a recorded image sequence with a video camera, it saves the scanning time compared with refracted near-field method [9] or near-field scanning method [15,16]. The modified end-fire coupling method demonstrates a simple and rapid way to reconstruct the refractive index profile of a small-core single-mode fiber.

Conventionally, a coherent laser source is used in measuring the fiber images. However, to avoid being subject to the obstruction of the speckles in the cladding region, the single-mode fiber under test is usually bent rather than straight during measurement. Nevertheless, bend-induced variation in the refractive index profile can distort the mode field distribution [17,18], which is an important issue needed to be solved in reconstructing the fiber index profile.

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Previous work has also shown to overcome the speckles on the optical pattern of an optical fiber by reducing the coherency of the laser light [19–22]. With a rotating diffuser that transforms the coherent laser source into a partially coherent light source [23], more uniform fiber cross-sectional images with higher image qualities can be obtained. Since the size of the laser beam launched on the diffuser plate made of celluloid is much larger than that of the single uniform domain of the diffuser, the laser beam that passes through the diffuser splits into many tiny light spots, and the spatial coherency is thus lowered [23]. The observed optical patterns of the scattered light spots behind the diffuser at various distances from the laser focus have been demonstrated in previous work [24]. Better fiber images may help us explore and understand more basic characteristics of an optical fiber.

Since better fiber images can be obtained with lower coherence transformed light, in this work, at first, a partially coherent light source is used in measuring fiber images of a straight fiber and reconstructing its refractive index profile. We show that the speckles of fiber images of a straight fiber can thus be overcome with partially coherent light, and its corresponding index profile can then be reconstructed successfully. On the other hand, if the coherent laser light is coupled into a bent fiber, most of the speckles can be eliminated since the higher-order cladding modes can leak out of the fiber cladding at the bending region [25,26]. Nevertheless, after coupling coherent laser light into a bent fiber, slight distortion due to fiber bending and mode transition can be seen from the measured fiber image as well as the reconstructed index profile, which contradicts the expected refractive index profile of the test fiber with a fiber coil in the middle. Therefore, for comparison, in this work the refractive index profile of a bent fiber is also measured by coupling partially coherent light into the test fiber. We find that the symmetry of reconstructed index profile of a bent fiber can be greatly improved when the coherent laser source is combined with a rotating diffuser. The reconstructed index profile obtained in this way more approaches the originally expected refractive index profile of the test fiber.

2. Methods

2.1. Experimental system

A small-core single-mode fiber (Thorlabs SM600, cutoff wavelength ~550 ± 50 nm) with step index profile and total length 210 mm is measured at wavelength of 632.8 nm. This fiber has a ~3.6 μm core diameter, 125 μm cladding diameter, 245 μm coating diameter, and estimated mode field diameter of 4.3 μm at 633 nm. The measurement setup of direct (end-fire) coupling of coherent laser light to a straight fiber is shown in the insets of Fig. 1 with dashed lines. A He–Ne laser at 632.8 nm (JDSU 1103-P) is end-fire coupled to the test fiber with a 10× focusing objective lens (Olympus RMS10×). The fiber image is focused with a 100× oil immersion objective lens (Olympus PLN100×O) on an *X–Y–Z* stage for high image resolution and then captured with a charge-coupled-device (CCD) camera (PCO pixelfly qe). Speckles can be seen clearly in the cladding region of the fiber image, as shown in the inset of Fig. 1(a) above the computer screen. To obtain a partially coherent light source, a rotating diffuser with a rotary motor controlled at 43 Hz is added behind the laser light source. The resultant averaged duration of the tiny light spots among the highly fragmented and fast fluctuating laser beam is much smaller than the response time of the CCD camera. The diffuser is utilized to fragment the laser beam into many tiny light spots and to decrease the spatial coherence of the laser light. Although the rotation of the diffuser somewhat decreases the temporal coherence of the transformed laser light, its degree of temporal coherence is still rather high since the rotation speed of the diffuser is far smaller than the propagation speed of the light. The rotation of the diffuser may increase the fiber image uniformity and improve the fiber index profiling, which is also related to the exposure time and averaging settings of the used CCD camera. Fig. 1 shows the measurement setup of a straight fiber image using a partially coherent light source. Before entering the diffuser, the laser beam is first expanded and then focused onto the diffuser for better fiber image quality. Three plano-convex lenses (labeled 1, 2, and 3 on Fig. 1) with focal lengths $f_1 = 50$ mm, $f_2 = 150$ mm and $f_3 = 50$ mm are used. Since the coherency of the laser light source is reduced after penetrating the rotating diffuser, the interferences between higher-order modes in the fiber cladding no longer look like a fixed optical pattern. All the light spots move and change randomly such that the averaged light intensity appears to be smoothly distributed [19–22]. The speckles of the fiber mode image are thus overcome when measuring a straight fiber with partially coherent light, which can be seen in the inset of Fig. 1(b) on the computer screen.

For comparison, a bent fiber (bend diameter ~15 mm) is also measured with a coherent and a partially coherent light sources, respectively, with the same setup as shown in Fig. 1. The bend diameter setting is chosen to make sure that most of the speckles at the fiber cladding can be eliminated sufficiently. Furthermore, the bending radius is chosen larger than the short-term bend

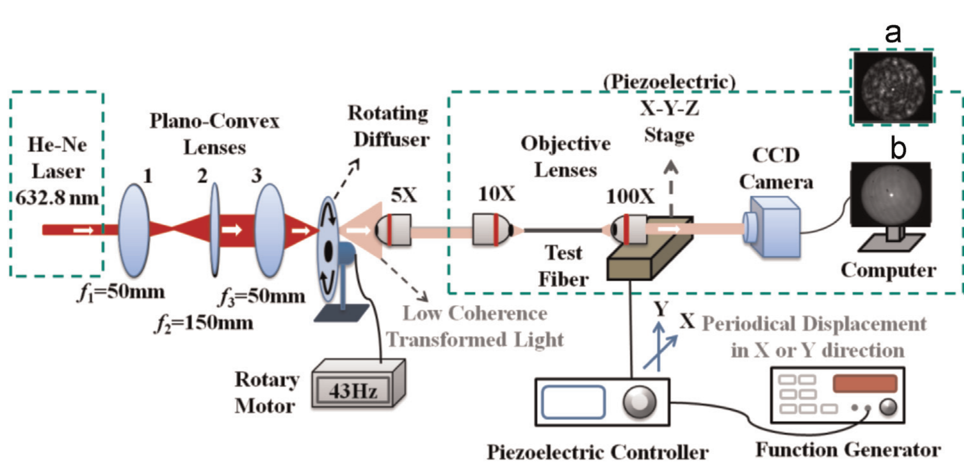

Fig. 1. Measurement setup of guided modes of a straight fiber with a modified end-fire coupling method under partially coherent light excitation. (Inside dashed lines: Measurement of fiber modes with a direct coupling method under coherent light excitation. Insets: Cross-sectional fiber mode images of a straight fiber with (a) a coherent and (b) a partially coherent light sources, respectively.)