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Measurement of spatial refractive index distributions of fusion spliced optical fibers by digital holographic microtomography

Feng Pan, Yating Deng, Xichao Ma, Wen Xiao *

Key Laboratory of Precision Opto-mechatronics Technology, School of Instrument Science and Optoelectronics Engineering, Beihang University, Beijing 100191, China

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ABSTRACT

Digital holographic microtomography is improved and applied to the measurements of three-dimensional refractive index distributions of fusion spliced optical fibers. Tomographic images are reconstructed from full-angle phase projection images obtained with a setup-rotation approach, in which the laser source, the optical system and the image sensor are arranged on an optical breadboard and synchronously rotated around the fixed object. For retrieving high-quality tomographic images, a numerical method is proposed to compensate the unwanted movements of the object in the lateral, axial and vertical directions during rotation. The compensation is implemented on the two-dimensional phase images instead of the sinogram. The experimental results exhibit distinctly the internal structures of fusion splices between a single-mode fiber and other fibers, including a multi-mode fiber, a panda polarization maintaining fiber, a bow-tie polarization maintaining fiber and a photonic crystal fiber. In particular, the internal structure distortion in the fusion areas can be intuitively observed, such as the expansion of the stress zones of polarization maintaining fibers, the collapse of the air holes of photonic crystal fibers, etc.

1. Introduction

Optical fibers and fiber devices are playing a significant role in applications as diverse as telecommunications, medicine, and industrial and biomedical sensing [1,2]. Additionally, in the recent decade photonic crystal fibers (PCFs) [3] have been developed and have an attractive prospect in the applications of fibers and fiber devices [4]. However, in most applications the practicality of fiber-based devices depends on whether they can be connected between optical fibers, such as long-distance transmission, electric field sensors [5,6], temperature sensors [7], polarizers [8] and optical fiber gyroscopes [9]. Therefore, the inspection of fiber splicing quality is essential in designing optical fiber devices as well as improving their fusion process [10,11]. The optical time-domain reflectometer (OTDR) and the optical continuous wave reflectometer (OCWR) are generally used to analyze the optical splicing loss [12,13]. However, these results are not intuitive and can hardly be used to distinguish the exact reasons for the change of optical fiber properties in the fusion region. The refractive index (RI) distribution directly reflects the three-dimensional (3D) internal structures of fibers. So it is one of the key parameters for quality assessment of optical fiber splicing.

Digital holographic microtomography (DHMT) provides efficient access to quantitative 3D distributions of RI of transparent or translucent objects [14]. In the technique, an optical field transmits through an object at various illumination directions and a set of projection phase images are obtained by digital holography (DH). Then the phase data are numerically processed using tomographic reconstruction algorithms, e.g. filtered backprojection (FBPJ) and filtered backpropagation (FBPP), to retrieve 3D distributions of RI. Due to the advantages of non-destructive, high-resolution and full-field imaging [15–17], DHMT has been playing a critical role in inspections of mechanical and geometrical parameters of optical fibers. Jeon and Hong applied DHMT to measure the RI distributions of a 4-hole PCF and a double cladding optical fiber, in which the unwanted axial movement of the object is corrected by numerical focus [18]. Kozacki et al. explored an integrated system of DHMT by using high frequency gratings, and obtained the internal RI distribution of a multimode fiber [19]. Lin and Cheng proposed a coaxial rotation approach to avoid mechanical disturbance of the sample, and measured the RI distribution of the fusion splice between a single mode fiber and a polarization maintaining fiber [20]. Pan et al. demonstrated experimental results of geometric parameters of a single mode fiber and a polarization-maintaining fiber by DHMT [21,22].

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* Corresponding author.
E-mail address: xiaow@buaa.edu.cn (W. Xiao).

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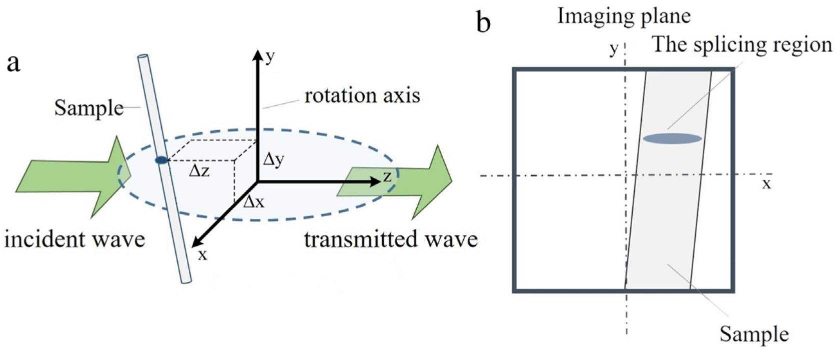

Fig. 1. Illustration of the rotation correction: (a) the deviation between the actual position of the fiber and the rotation axis; (b) actual deviation in the imaging plane.

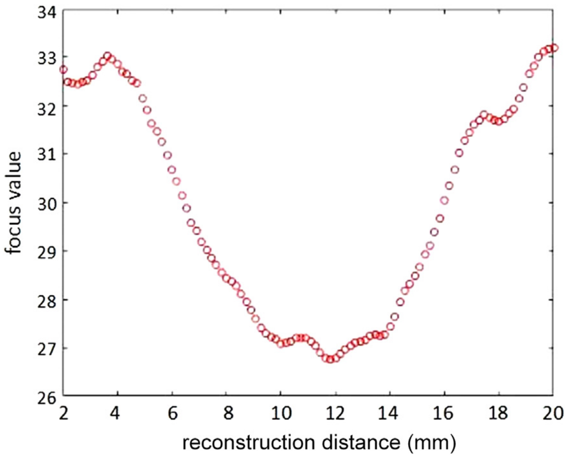

Fig. 2. The gray-value focusing criterion for refocusing the amplitude image of a SMF.

Kostencka et al. proposed a modified DHMT and observed a polymer microtip manufactured by a single mode optical fiber, in which the coherent noise in the phase data can be suppressed with autofocus correction [23,24]. Ma et al. proposed an improved DHMT by multiple numerical reconstructions so as to extend the depth of focus, and inspected a four-core optical fiber and a large mode optical crystal fiber [25]. So far, many research efforts have been devoted to improve the performance of tomographic reconstruction by numerical refocusing to the best focus plane [26] and by minimizing the radial run-out [27] due to the unwanted shift of the object during rotations. However, the phenomena of axial dislocation and separation, cladding diameter inconsistencies, angular displacement, etc. may occur in the fusion splicing process. Thus the symmetric structures of optical fibers are damaged in the splice regions. Considering the imperfection of rotation mechanism and the asymmetric structures of fused fibers, the fiber splicing interface periodically moves in three directions in the field of view, including the vertical, lateral and axial directions in measurement process. It is noted that the vertical error is an additional essential factor in comparison with the measurement of an intact fiber.

In this paper, we propose a numerical method to compensate the lateral, axial and vertical errors in rotation measurement. In this method, the axial error is corrected by refocusing of the 2D phase images with a holographic autofocusing technique, and edge-detection and image-registration algorithms are employed to compensate the lateral and vertical errors. All the projection phase images are aligned in the focusing plane. So accurate sinograms can be generated for tomographic reconstruction. In addition, we present a setup-rotation scheme of DHMT to record full-angle digital holograms. In this setup, the laser source, the optical system and the image sensor are arranged on an optical breadboard and synchronously rotated around the fixed object during the measurement procedure. Compared with the object-rotation scheme, this architecture avoids the effect of mechanical disturbance on the object suspended in a liquid medium. Finally, we measure the 3D RI distributions of the integral joint regions between different types of fibers, including the fiber splices between a single-mode fiber (SMF) and a multi-mode fiber (MMF), an SMF and a bow-tie polarization maintaining fiber (Bow-Tie PMF), an SMF and a panda polarization maintaining fiber (Panda PMF), especially an SMF and a PCF. As a result, the internal microstructures in the splice regions are clearly observed. This contributes to assess the quality of fiber splicing and improve the fusion methods.

2. Method for rotation error correction

In order to acquire full-angle projection data, holograms are recorded from a series of directions with an electronic image sensor such as a CCD/CMOS camera [28]. After that, a few important steps are necessary for numerical reconstruction. First, the so-called hologram apodization is carried out to avoid diffraction ripples on the reconstructed object wave [29]. Second, a spatial filter is applied in the Fourier spatial frequency domain to isolate the high-intensity zero-order term and the twin image term in an off-axis hologram [30]. Third, the phase aberrations of the imaging system are compensated by the numerical aberration correction method with a reference hologram [31]. Finally, the projection amplitude and phase images are retrieved using the convolution propagation algorithm [32]. However, there are inevitable mechanical imperfection in the actual rotation measurements, including inaccurate coaxiality and perpendicularity between the rotation axis and the inertia axis of the fused fiber. Moreover, the fusion splice would change the geometries of coupled fibers, and damage the symmetry and straightness. So the position of the fiber splicing interface is unstable and periodically changes in rotation measurement process. Because the rotation is relative between the fused fiber and measurement system, the fiber rotation is assumed for the sake of analysis. The unwanted movement can be separated into the lateral (ΔX), axial (ΔZ) and vertical (ΔY) components, as shown in Fig. 1. The components ΔX and ΔY cause respectively the deviation of the fused fiber in the x and y directions with slight inclination in the field of view and without causing defocusing. Considering the limited depth of focus of the microscopic imaging system, the component ΔZ causes an out-of-focus movement and induces a strong defocusing of the image.

The effects of the unwanted movement are corrected in three steps as follows. First, nonzero ΔZ is compensated at the stage of holographic reconstruction by choosing a proper reconstruction distance. Here, the gray-value indicator [33] is chosen to apply on the phase image to determine the best in-focus plane from a set of reconstructed images along the optical axis. As can be seen from Fig. 2, the gray-value curve is presented when the reconstruction distance is changed from 2 to 20 mm for the amplitude image of an SMF, and the best focus is obtained at the lowest point of the curve corresponding to 11.81 mm.