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Microtomography of the polarization-maintaining fiber by digital holography

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ABSTRACT

We report the experimental results of structural parameters measurement of the polarization-maintaining fiber (PMF) by the use of digital holographic microtomography. First, digital holography (DH) in microscopy configuration is used to record complex transmitted fields under various angles of incidence, and then the Fourier diffraction tomography algorithm is applied to reconstruct the 3-D refractive index (RI) distribution of the PMF. According to the 3-D map of RI, we can further get geometric parameters of the PMF by the related edge detection algorithm of image processing. The experimental results show that, the diffraction tomography algorithm is superior to the reconstruction algorithm based on Fourier slice theorem in terms of exhibiting reasonable RI distribution and respecting the dimensions of the PMF. It provides a new way for the non-destructive micromeasurement of the PMF.

1. Introduction

Polarization-maintaining fiber (PMF), due to its strong ability to maintain the polarization state of the input linearly polarized light and good compatibility with single mode fibers, is widely used in interference sensing, coherent optical communication, etc [1,2]. In practice, the PMF geometry is very important, especially in the case of PMF's accurate docking, because mismatches will lead to optical power attenuation and intrinsic coupling loss. High-performance PMF requires strict quality control, which is inseparable from the proper selection of fiber parameters measurement method. Currently, the artificial identification method [3], the image shearing method [3,4], the near-field imaging method [3,5], the method based on forward near-axis far-field interference [3,6], the method based on machine vision [3,7] and so on, are generally used to measure the geometric parameters of PMF. However, the effective implementation of these methods either requires expensive precision instruments or needs to cut and polish the cross section of PMF, which must strictly control the perpendicularity of cross section of PMF to avoid large measurement errors. Therefore, in the field of industrial control, we need to find a kind of low cost, high efficiency, non-contact and nondestructive measurement method to accurately measure the structural parameters of PMF.

Digital holographic microtomography [8–14] is a new type of 3-D refractive index (RI) imaging technology which is put forward and developed in recent years. The basic idea of this technique is to combine digital holography (DH) with computed tomography (CT) technology. In DH, the quantitative measurement of phase distribution from single hologram reveals not the 3-D internal distribution of the phase-type object but a phase shift resulting from a mean RI accumulated over the object thickness. In other words, the reconstructed phase distribution loses the structural details of the object along the beam propagation direction. In order to completely and accurately obtain the internal structure of the object, it is necessary to combine tomography technique. Based on the projection reconstruction principle of CT technology, the 3-D structure of the phase-type object can be reconstructed cross-section by cross-section, by recording holograms resulting from the interference between the object wave and the reference wave under multidirectional illumination. Comparing with other tomography techniques, digital holographic microtomography has the advantages of nondestructive, non-contact, high-resolution, high-contrast, full-field imaging and auto-focus [14–18]. Therefore it is especially suitable to be used to reconstruct the cross-sectional structure of PMF so as to further obtain its geometric parameters and RI distribution.

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The accuracy of measurements depends on the reconstruction algorithm. For a weakly diffracting object, due to its very small RI variation, the light propagation across the object can be assumed to remain parallel to the optical axis, and then the filtered backprojection algorithm derived from the Fourier slice theorem can be applied [19]. This is often a good approximation for points close to the plane of focus. However, since the effect of diffraction is ignored and the large numerical aperture (NA) of the objective lens gives a small depth of focus, this approximation will cause the deterioration of image quality at any locations away from the focal plane, especially when the object is thick compared with the depth of focus of the imaging system. Therefore, the projection approximation is inaccurate for high-resolution microscopic imaging. In this case, the diffraction tomography algorithm which takes diffraction into account is more suitable to be used for reconstruction. This is derived from Fourier diffraction theorem proposed by Wolf [20], which allows small diffraction effects in the object under the condition of satisfying the first-order Born or the Rytov approximation to make the relation between the complex RI of the object and the measured field linear [19].

In previous work, we have successfully used the digital holographic microtomography to reconstruct the internal structure of single-mode fibers by employing the diffraction tomography algorithm [21]. Because the single-mode fiber is rotational symmetry with respect to any angle, the operation of rotating the object can be omitted. Just one hologram needs to be recorded to perform tomographic reconstruction. The experimental results are satisfactory. In this work, we further report the experimental implementation of digital holographic microtomography to achieve the measurement of internal structure of the PMF. Unlike the single-mode fiber, the cross section of PMF is not circular symmetry. The experimental platform settings, experimental data recording and data processing for PMF measurement are more complicated than that for single-mode fiber measurement presented in [21]. The measurement is completed by the following steps: first, we use DH in microscopy configuration to record complex transmitted fields under various angles of incidence, then Fourier diffraction tomography (FDT) algorithm is applied to reconstruct the 3-D RI distribution of the PMF, and finally according to the 3-D map of RI, we can further get geometric parameters of the PMF by the relate edge detection algorithm of image processing. Experimental results exhibit reasonable reconstruction quality and precisely respect the PMF's parameters provided by the manufacturer.

2. Principle of digital holographic microtomography based on Fourier diffraction theorem

According to Wolf's original theory of diffraction tomography [20,22], if the interaction of an object and a field is modeled with the wave equation, a tomographic reconstruction approach based on the Fourier diffraction theorem is possible for weakly diffracting objects. With the scalar field assumption, the propagation of light field through an inhomogeneous medium can be described by the wave equation as follow:

$$(\nabla^2 + k_0^2)U(\vec{r}) = -O(\vec{r})U(\vec{r}), \tag{1}$$

$O(\vec{r})$ is known as the object function given by the following equation:

$$O(\vec{r}) = k_0^2(n(\vec{r})^2 - 1), \tag{2}$$

where $k_0 = 2\pi/\lambda_0$ is the wave number in the free space, $n(\vec{r})$ is the object spatial distribution of the RI to be reconstructed. If the total scalar field $U(\vec{r})$ can be regarded as the sum of the incident field and the scattered field: $U(\vec{r}) = U_i(\vec{r}) + U_s(\vec{r})$, the wave equation becomes

$$(\nabla^2 + k_0^2)U_s(\vec{r}) = -O(\vec{r})U(\vec{r}), \tag{3}$$

Based on Green's theorem, the formal solution to Eq. (3) can be written as

$$U_s(\vec{r}) = \int G(\vec{r} - \vec{r}')O(\vec{r}')U(\vec{r}')d^3\vec{r}'. \tag{4}$$

Assuming that the RI of the scattering object varies slowly, the first-order Born approximation is obtained by replacing the total field $U(\vec{r})$ with the incident field $U_i(\vec{r})$, then Eq. (4) can be written as:

$$U_s(\vec{r}) \approx \int G(\vec{r} - \vec{r}')O(\vec{r}')U_i(\vec{r}')d^3\vec{r}'. \tag{5}$$

This approximation provides a linear relation between the object function and the scattered field. By taking Fourier transform of both sides of Eq. (5), we can obtain the following relation, known as the Fourier diffraction theorem:

$$\widehat{U}_s(k_x, k_y; z = 0) = \frac{\pi}{ik_z}\hat{O}(K_x, K_y, K_z), \qquad k_z = \sqrt{k^2 - k_x^2 - k_y^2}. \tag{6}$$

Here, $\widehat{U}_s$ is the 2-D Fourier transform of the scattered field and $\hat{O}$ is the 3-D Fourier transform of the object function. According to Fourier diffraction theorem, for each illumination angle, the Fourier transform of the 2-D measured scattered field is mapped onto a spherical surface in the frequency domain of the 3-D object function. This spherical surface is called the Ewald sphere. The measure of the scattered field in all possible illumination directions makes it possible to completely cover the Ewald limiting sphere. After completing the mapping, we can take the inverse Fourier transform of $\hat{O}$ to get the 3-D distribution of the complex RI of the object. However, for a weakly scattering object having a cylindrical structure (such as PMF), its RI distribution is the same along the direction of perpendicular to the cross-section, namely the direction of rotation axis (x axis). Tomography reconstruction can be further simplified in terms of the computational amount and the complexity. Because when the parallel light incident to the cylindrical object along the direction of perpendicular to the rotation axis, the light diffraction only occurs within the cross-section of the object, so we can implement 2-D diffraction tomography algorithm to reconstruct a cylindrical object cross-section by cross-section. In this case, the Fourier transform of 1-D scattered projection data gives the values of the 2-D Fourier transform of the object function along a semicircular arc in the frequency domain. When the Fourier slice theorem is considered, the arc in the frequency domain becomes a straight line, as illustrated in Fig. 1. According to the abovementioned reconstruction principle in diffraction tomography, there are two computational strategies, namely, the frequency domain interpolation (direct Fourier inversion) and the space domain interpolation (filtered backpropagation algorithm) to be applied to realize the diffraction tomography. In this work the latter method was used.

To achieve tomographic reconstruction, the object needs to be rotated step by step, covering a total angle of 360°. We can use DH in microscopy configuration to record holograms at various object orientations, and then the complex wavefront $U(x, y; \theta_i)$ at the image plane can be reconstructed by numerical reconstruction methods, where $\theta_i = \{0, \Delta\theta, 2\Delta\theta \cdots\cdots, 360^0 - \Delta\theta\}, \Delta\theta$ is the rotating step angle. The measured field $U(x, y; \theta_i)$ which provides the amplitude image and the phase image can be used as the scattered field $U_s(\vec{r})$ required for diffraction tomography. The maximal spatial resolution of the reconstructed RI distribution depends on the rotating step angle $\Delta\theta$. In our experimental setup, the 2° step is sufficient to meet the spatial resolution requirement.