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Characterization of optical fiber profile using dual-wavelength diffraction phase microscopy and filtered back projection algorithm

Mohammad Reza Jafarfard *, Mohammad Hossein Mahdieh

Department of Physics, Iran University of Science and Technology, Narmak, Tehran 19395-5531, Iran

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ABSTRACT

We present a measurement scheme of the refractive index profile of optical fibers which does not require accurate index oil match using dual wavelength diffraction phase microscopy. Using dual wavelength algorithm, we solved phase wrapping problem caused by large optical path length difference between the optical fiber and its medium and final phase image was obtained without 2π ambiguity. The index profile was obtained by the filtered back projection algorithm that applies inverse Radon transformation of the phase profile matrix. As an example, a single mode fiber with a known index profile was measured by using this method. The measured profile is well agreed with index profile of the preform, which had been designed by a preform analyzer before the fiber being fabricated from the preform.

1. Introduction

Since fiber properties such as the mode profile, dispersion, and cutoff wavelength can be extracted from the refractive index profile of fiber, accurate measurement of the index profile has become an important issue since the last decades. Several methods have been proposed for determining the refractive-index profiles of optical fibers [1–4]. The most widely used technique, is the refracted near field (RNF) method which is an industry standard index-profiling instruments [5]. However, it is unable to measure rapidly varying refractive index along the fiber axis. Furthermore, the technique is destructive since the fiber must be cleaved. Aside from RNF, there are some other techniques such as the refractive inversion of fundamental mode-field measurements [6], studying the light scattered by the fiber [7] have been also used to determine index profile of optical fibers which are suffering from disadvantages of low speed or being destructive. Among these method, interferometric techniques can be advantageous methods in fiber profiling because they possess high accuracy and speed as well as being non-destructive [8–10]. Nevertheless, this technique needs image processing to extract the phase data in which numerically unwrapping processes are involved. Since optical fibers are large phase objects, the unwrapping problem is an issue in interferometric methods. Immersing fiber in index match oil is a common method to avoid wrapping problem in phase imaging [9,11]. However, since the refractive index of immersion medium should be very close to the index of fiber, finding proper index match oil can be a challenging work in some cases.

* Corresponding author.
E-mail address: mrjafarfard@iust.ac.ir (M.R. Jafarfard).

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In this paper, we demonstrate another application of our dual-wavelength diffraction phase microscope (DW-DPM) [12] which can be used in a real time and stable determination of refractive index profile of optical fiber without any demand for very close index matching oil. In this method, by simultaneous measurement of wrapped phase images with two wavelengths, dual wavelength algorithm is applied to solve phase wrapping problem (caused by large size of optical fiber). Therefore, the final phase image can be extracted without 2π ambiguity. Due to common path geometry of our DW-DPM, real-time and reliable phase image can be obtained. Since the classic formula of the inverse Abel integration may comprise enormous measurement errors in the vicinity of the origin, we propose filtered back projection algorithm as a new scheme to extract index profile of fiber from the phase image matrix.

2. Theory

2.1. Dual wavelength unwrapping

Several unwrapping algorithm has been proposed for several applications in digital holography within the last decade Dual illumination methods were proposed for resolving large step objects. However, these methods suffer from enhancing noises [13–14]. Multiple wavelengths algorithm methods could precisely solve wrapping problem for limited size of phase object [15–17]. For large transparent samples, measured phase map "φ_i" which is converted to optical path length difference (OPD) profile may consist of several ramped points in which the OPD is equal to the wavelength. To solve ambiguity of phase due to ramped points, an integer factor of 2π should be added to the phase which is described by $\Phi i = 2\pi m_i + \varphi_i$. Where $i = 1,2$ and corresponded to each measurement for two wavelengths, φ_i is measured wrapped phase, m_i is an integer and must be found so that the actual value of phase "Φi" is obtained. By measurement of two wrapped phases for each wavelength and subtracting Φ_2 from Φ_1, the OPD can be found by:

$$OPD = \Lambda\left[\frac{1}{2\pi}(\varphi_1 - \varphi_2) + (m_1 - m_2)\right] \tag{1}$$

where the term $\Lambda = \frac{\lambda 1 \lambda 2}{\lambda 2 - \lambda 1}$ is known as the “synthetic” or “beat” wavelength and λ_2 and λ_1 are two incident wavelengths. Assuming that $\lambda_2 > \lambda_1$, then m_1 cannot be less than m_2. If we assume that the total OPD of the object is less than the synthetic wavelength, then in Eq. (1), the term in the bracket must be positive and less than 1. In addition, the first term in the bracket is between −1 and 1. Hence, the unwrapping algorithm should be written in following condition: Ïf first term of bracket is positive, (m_1-m_2) must be equal to 0. Otherwise, (m_1-m_2) must be equal to 1.B̈y this algorithm one can extract the final unwrapped OPD.

Filtered back projection algorithm

In quantitative phase imaging systems the measured phase $\Phi(x, y)$ can be expressed as:

$$\Phi(x, y) = \frac{2\pi}{\lambda}\int \delta n(x, y, z)dx \tag{2}$$

Where $\boldsymbol{\lambda}$ is the wavelength of the light source and $\delta n\,(x, y, z)$ is the 3D refractive index spatial distribution difference between the sample and its surrounding medium. In a standard tomographic reconstruction, one must record two-dimensional planar phase distribution for different sample orientations covering all 180° direction. Based on Fourier slice theorem [18], the summation of Fourier transformation of phase in all direction is 3D refractive index $n\ (x,\ y,\ z)$ in frequency domain. Therefore, by inverse Fourier transformation of this summation, the 3D refractive index of the sample can be obtained by

$$n(x, y, z) = \frac{\lambda}{2\pi}FT^{-1}\sum_{\theta=0}^{180} FT(\Phi_\theta(x, y)). \tag{3}$$

Where *FT* is Fourier Transformation and $\Phi_\theta\,(x)$ is the measured phase in θ direction. This method is a well-known technique in X-ray Computed Tomographic (CT) imaging [18]. The calculations can be performed using the standard inverse radon transform from the MATLAB programming environment.

Extraction of refractive index of fiber from the phase image

The cladding part of optical fibers usually made by silica glass with known and constant refractive index over space. However, the core has unknown and variable refractive index over space. Moreover, fibers are obviously symmetric in their length (y direction). Therefore $\Phi(x)$ which is a cross section of the measured phase image can be written by Abel transformation as [11]:

$$\Phi(x) = \frac{4\pi}{\lambda}\int_x^R \delta n(r)\frac{rdr}{\sqrt{r^2 - x^2}} = \frac{4\pi}{\lambda}\int_x^a \delta n'(r)\frac{rdr}{\sqrt{r^2 - x^2}} + \frac{4\pi.\delta n_0}{\lambda}\int_x^R \frac{rdr}{\sqrt{r^2 - x^2}}. \tag{4}$$

Where a and R are radius of the core and cladding respectively. The parameter δn_0 is the refractive index difference between cladding and medium and $\delta n'$ is the core refractive index difference. The second integral is simply equal to $\Phi_0(x) = \frac{4\pi.\delta n_0}{\lambda}\sqrt{R^2 - x^2}$. Therefore, the phase corresponding to the core would be obtained by subtracting calculated phase