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Ultrahigh-accuracy measurement of refractive index curves of optical materials using interferometry technology

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ABSTRACT

A spectral-domain white-light interferometry and a two-slit laser interference system for measurement of the refractive index curves of optical materials over a wide wavelength range was reported. The interferometry was employed to measure the group refractive index of the materials. An integral algorithm was proposed to calculate the refractive index curve from the obtained group refractive index. The integration required the refractive index value for a specific wavelength which could be achieved by the two-slit laser interference system. A spectrum correction method was used for calculation of group optical path difference. The proposed method realized an ultrahigh accuracy measurement of refractive index curve better than 0.0002, making it attractive for the application in the determination of optical parameters of new materials.

1. Introduction

Refractive index is an optical parameter which is determined by the molecular polarizability of the medium and it gives insight to the interaction of light with matter and the structure of substances [1]. Dispersion is the physical property of a substance that describes the wavelength dependence of its refractive index. Dispersion leads different velocity at different wavelength, it greatly effects optical elements and optical waveguide performance. Simple example is the chromatic aberration of the optical lens. The refractive index curve measurement has been studied by a variety of optical experimental methods.

The most common measurement method is based on refractometry, in which the refractive index curve as a function of wavelength has usually been obtained through numerical fitting of some discrete values of the index. Each of them was calculated by Snell's law from deflection angle of light pass through the optical system that includes a sample [2–4]. However, these methods need a variety of procedures to measure the refractive index curve. It's not a convenient way.

A new approach to measure refractive index is spectrally resolved white-light interferometry (SRWLI) [5], in which the group refractive index [6] of each wavelength is acquired by spectral interferogram analysis [7]. For broadband lights, the group refractive index is defined as the ratio of group velocity of light in vacuum and the one in medium (group velocity refers to the propagation velocity of energy and information in the medium). However, refractive index is the ratio of velocity of light in vacuum and in medium. This is the difference between the definition of group refractive index and the refractive index. A Michelson interferometer was illuminated with a broadband light source and the specimen was inserted into its test arm to obtain spectral interferogram [8,9]. In addition, a Mach-Zehnder interferometer was employed to extend to two-dimensional spectral interferometry [10,11]. In recent years, there is also a method to simultaneously measure the group refractive index and thickness of sample by using this low coherent interferometry technology [12–14]. However, it only obtained the equivalent value of the group refractive index for entire wavelength range, and it really don't give the refractive index information.

The group refractive index determines the propagation speed of the energy and signal of the beams in the material. On the other hand, the refractive index is the ratio of the propagation velocity in vacuum and material of monochromatic light. It determines the deflection angle of lights passing through the material interface. Therefore, the group refractive index and refractive index are two different parameters of material. To the best of our knowledge, refractive index curve measured by white-light interferometry has not been reported in the literature.

In the present work, a spectral-domain white-light interferometry

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system was utilized to obtain spectral interferogram. Subsequently, a spectrum correction method was used to achieve the wavelength-dependent group refractive index. We deduced the relationship between group refractive index and refractive index. From the relationship obtained, the refractive index value of a specific wavelength is required. A two-slit laser interference system was used to determine the refractive index of a certain wavelength. Finally, an integral algorithm was presented to obtain the refractive index curve from group refractive index. Refractive index curves of four optical materials were measured and presented.

2. Methodology of refractive index curve measurement

2.1. Group refraction index measured by a white-light interferometry

White-light interferometry is a measurement technique which uses broadband light interference. Interference occurs when both the two beams are spatially matched in size and orientation, and their optical path lengths are matched within the coherence length of the light source. The result of the interference is that the intensity of the merged beam changes periodically in space or in the spectral domain. The light intensity of system with the spectrometer as the collector can be described as [15]:

$$I_{(k)} = I_{1(k)} + I_{2(k)} + 2Re(\sqrt{I_{1(k)}*I_{2(k)}}*\exp(-i2\pi k*\Delta L)) \tag{1}$$

where $I_{1(k)}$ is the spectral density function of light source, k is the wavenumber (the reciprocal of wavelength), ΔL is the optical path difference (OPD) of two beams. Using Eq. (1), we could obtain the relationship between interference fringes number m or phase $\Delta\varphi$ and optical path difference (OPD) ΔL:

$$\mathrm{m}= \Delta\mathrm{L}*(k_1-k_0), \Delta\varphi = \mathrm{m}*2\pi \tag{2}$$

where k_1 and k_0 are respectively the maximum and minimum wavenumber for an interested wavelength range. Take an example, if the interested wavelength range is 600–1000 nm, it could realize nanometer accuracy measurement of optical path length using a high precision phase analysis or spectrum analysis.

When a dispersive glass sample is inserted into the system, the function can be changed as:

$$I_{(k)} = I_{1(k)} + I_{2(k)} + 2Re(\sqrt{I_{1(k)}*I_{2(k)}}*\exp(-i2\pi k*((n_{(k)}-1)*\mathrm{d}+ \Delta L))) \tag{3}$$

where $n_{(k)}$ is the wavenumber-dependent refractive index, d is the thickness of the glass sample. From Eqs. (2) and (3), we could calculation the group optical path length by counting the additional number of interference fringes in a wavenumber range. We could obtain

$$n_{g(k)} = \Delta\mathrm{L}/d + 1 \tag{4}$$

where $n_{g(k)}$ is the wavenumber-dependent group refractive index. It is noted here that, for a particular wavelength range, we could divide the whole range into many small parts to obtain the group refractive index for series of wavelength. We acquire the group refractive index curve by calculation the group refractive index in each part.

In order to obtain interference fringes number m in each small part, the Fast Fourier Transform (FFT) method is generally used. For the traditional FFT method, the spectral resolution is related to the length of the sample data according to the formula Δ f= 1/T. In order to improve the spectral resolution, increasing the number of sampling points is an option. However, due to the energy leakage effect [16] in the FFT procedure, the computational accuracy of interference fringes number m is not very high. To solve this problem, Hanning window was used in the FFT of a measured spectral interferogram, and then an energy-centroid discrete spectrum correction method was used to obtain precise determination of signal parameters such as frequency, and amplitude [16,17]. The detailed theory on energy-centroid discrete spectrum correction method can be found in Ref. [17]. This spectrum correction technique can accurately obtain the interference fringes number m in each small wavenumber range.

2.2. Relation between group refractive index and refractive index curve

Due to dispersion, Eq. (4) is in fact not calculating refractive index but group refractive index. Only when the refractive index of a material does not vary with wavelengths, the refractive index is equal to the group refractive index.

If the wavenumber changes from k_0 to k_1, the corresponding change of unwrapped phase can be deduced from Eq. (3) as

$$\Delta\varphi = 2\pi k_0(n_{(k_0)}-1)*d-2\pi k_1(n_{(k_1)}-1)*\mathrm{d} \tag{5}$$

Considering Eqs. (2), (4) and (5), the relationship between the group refractive index $n_{g(k)}$ and the refractive index $n_{(k)}$ could be expressed as [6]:

$$n_{g(k)} = n'_{(k)}*\mathrm{k}+ n_{(k)} \tag{6}$$

where $n'_{(k)}$ means derivation of $n_{(k)}$.

In order to obtain the refractive index, one option is using data fitting method. We could set the group refractive index function as:

$$n_{g(k)} = a_0 + a_1*k + a_2*k^2 + a_3*k^3 + ...+a_n*k^n + ... \tag{7}$$

Least square method could be used to fit the group refractive index curve to obtain the coefficients a_n. Then refractive index function could be calculated by

$$n_{(k)} = b*k^{-1} + a_0 + \frac{1}{2}a_1*k + \frac{1}{3}a_2*k^2 + \frac{1}{4}a_3*k^3 + ...+\frac{1}{n+1}a_n*k^n + ... \tag{8}$$

where k^{-1} is a general solution of differential Eq. (6) and b is arbitrary value. However, the value of b is very small, so we ignored it in the computation [18]. Moreover, the value of the coefficient a_n would become not stability as the increasing of the order of decomposition; this algorithm does not provide enough computational accuracy. There exist a theoretical error in the fitting of group refractive index and therefore, this fitting method could only get the approximate value of refractive index.

In the present work, an integral algorithm is proposed for calculating the refractive index as

$$n_{(k_0)}*k_0-n_{(k_1)}*k_1 = \int_{k_1}^{k_0} n_{g(k)}dk \tag{9}$$

This integral algorithm will not introduce any computational error and theoretical error. The precision of refractive index curve is only dependent on the accuracy of the experiments. Noted here that the refractive index value of a specific wavelength ($n_{(k_0)}$) is required for the integral algorithm.

2.3. Measurement of refractive index for a specific wavelength by two-slit laser interference method

Two-slit laser interference is a classical physical experiment. However, to the best of our knowledge, it has not been used for refractive index measurement. A laser beam with a known wavelength emits from the light source and pass through a single-slit sheet and then a two-slit sheet. Its diffraction pattern shown in an observation screen and the diffraction follows the Finel's law. The interference fringes will appear on the screen as

$$E_{(x)} = E_{0(x)}*\cos(2\pi x d_1/\lambda L_1) \tag{10}$$

where diffraction intensity function E_0 is related to the distance and width of two slits; x is the vertical coordinate on the observation screen; d_1 is the distance of two slits in two-slit sheet; λ is the wavelength of the laser; and L_1 is the distance between the two-slit sheet and the