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# Spectrally resolved white light interferometer for measuring dispersion in the visible and near infrared range

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ABSTRACT

We design a spectrally resolved interferometer to measure the refractive index of transparent samples over a broad spectral range of 400–1550 nm. The measuring device consists of a Michelson interferometer whose output is analysed by means of three fibre spectrometers: a homemade prism spectrometer which obtains the interferogram generated by the sample in the 400–1050 nm range, a homemade transmission grating spectrometer that measures the interferogram in the 950–1550 nm near infrared range, and a commercial Czerny-Turner spectrometer used to make high-precision measurements of the displacement between the Michelson mirrors. The whole system is illuminated by a white-light source with an emission spectrum similar to that of a black body. We test the instrument on solid and liquid samples achieving accuracy of up to $10^{-4}$ in the refractive index after fitting it with the Cauchy formula.

## 1. Introduction

In optics, dispersion refers to the dependence of the optical properties of a material or device upon wavelength. Material dispersion, or chromatic dispersion, which describes the wavelength dependence of the refractive index, concerns any phenomena related to refraction and therefore affects the efficiency of many optical systems operating in different spectral intervals. One important example is optical fibre communications where the data bit rate would be strongly limited if the broadening of the signal pulse due to dispersion during propagation was not minimized or compensated [1]. Dispersion also affects the operation of nonlinear optical devices: it is responsible for the temporal walk off, its characterization is essential to determine the phase-matching condition [2], and it can minimize the efficiency of four-wave mixing processes [3], to list some examples. In addition, it leads to chromatic aberration that affects optical imaging systems and especially optical microscopy [4]. The photonic crystal technology is affected by dispersion as well [5]; in particular, the guiding properties of photonic crystal fibres filled with liquids are very sensitive to the chromatic dispersion of the liquid [6]. Different endeavours in the laser technology [7], such as, pulse compression or propagation of increasingly shorter pulses, require precise knowledge of the behaviour of chromatic dispersion in certain wavelength ranges in the VIS-NIR region.

Therefore, accurate knowledge of dispersion is crucial when operating at different frequencies in the VIS-NIR spectral region in many fields of science and industry, including optical design, optical imaging, optical communication, laser physics, low-coherence metrologies, and ultrafast optics. Additionally, dispersion can be used for sensing [8]; to obtain information about various physical properties and chemical composition, for example, impurities content or environmental conditions; it is also essential for the development of theoretical and numerical physical models.

From the pioneering work of Sainz and co-workers [9–11], the analysis of interference of incoherent light in the spectral domain (spectrally resolved white-light interferometry, SRWLI) has been shown to be a powerful tool to measure material dispersion over a broad spectral range [12–21]. The characterization of materials requires covering the widest possible spectral range while preserving high resolution, a challenge that must be overcome in a proper way. For example, Hlubina [21] used a low-resolution spectrometer to obtain the group and differential group indices over the 500–900 nm spectral range by sequentially evaluating the stationary phase point position as a function of the interferometer path length difference in air; the achieved accuracy for the differential group index was $\sim 7 \times 10^{-5}$. Delbarre et al. [15] processed three interferograms including a stationary phase point to get the group index and estimate the refractive index from 540 to 660 nm; the relative accuracy was $\sim 9 \times 10^{-4}$ for the group index and $5 \times 10^{-4}$ for the refractive index. Reolon et al. [17] used a broadband supercontinuum source with high degree of

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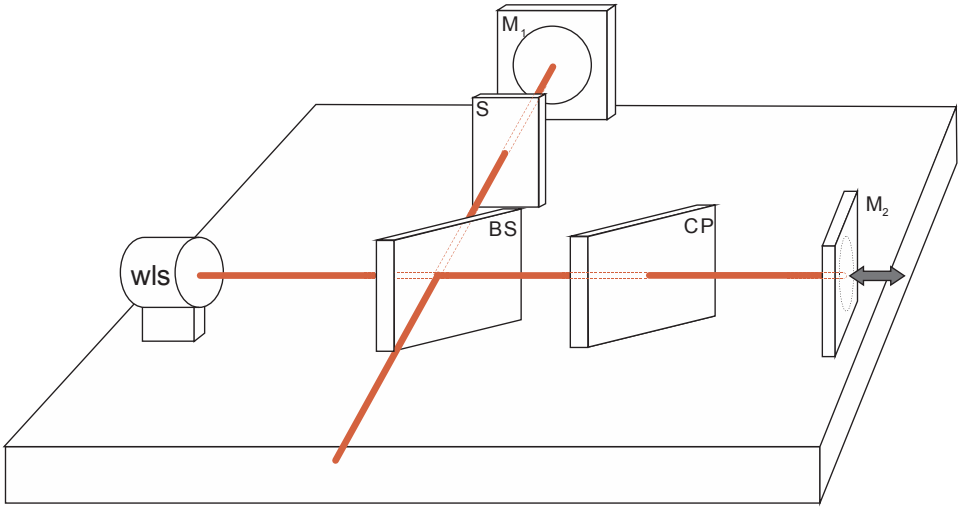


**Fig. 1.** Typical Michelson interferometer with the sample, S, and a fixed mirror, $M_1$, in one arm and a moving mirror, $M_2$, in the other arm. WLS, white light source; BS, beam splitter; CP, compensating plate.

spatial coherence to increase the fringe visibility and measured the group index from 530 to 800 nm in a single acquisition, attaining an accuracy of $3 \times 10^{-4}$. Recently [20], we measured the refractive index of solid samples in a single acquisition in the spectral range of 400–1000 nm. The accuracy of the results was $\sim 10^{-4}$ for the group index and below $10^{-4}$ for the refractive index. We also applied SRWLI to measure the refractive index of 14 imidazolium-based ionic liquids [22] in the same spectral range with accuracy better than $2 \times 10^{-4}$.

In this paper, we describe the measurement of the dispersion of solid and liquid samples in a very broad range of 400–1550 nm. To achieve this goal, we incorporate a second spectrometer into our apparatus to obtain data for long wavelengths. In Section 2, we review the principles of SRWLI, highlighting the main issues arising when applying this technique; in Section 3, we describe our device; in Section 4, we detail the different steps of the experimental procedure; in Section 5, we present and discuss the results obtained with different samples; finally, in Section 6, we present our conclusions.

## 2. Theoretical foundation

In this section, we consider a Michelson interferometer (see Fig. 1) with the sample to be measured in one arm (the sample arm) and a moving mirror in the other arm (the reference arm), which compensates the dispersion generated by the sample. At the output of the interferometer, we obtain the irradiance resulting from the interference of the beams travelling in its two arms. Considering light of wavelength λ, a sample of thickness $d$, and a displacement in air between the interference mirrors $l$, we get:

$$I(\lambda) = I_0(\lambda)[1 + V(\lambda)\cos\varphi(\lambda)], \tag{1a}$$

$$\varphi(\lambda) = 4\pi\,[d(n - n_{air}) - n_{air}\,l]/\lambda, \tag{1b}$$

where $I_0(\lambda)$ is the background spectral irradiance, $V(\lambda)$ is the fringe visibility, $\varphi(\sigma)$ is the phase difference between the beams of the interferometer, and $n_{air}$ and $n$ are the refractive indices of air and the sample, respectively, calculated at wavelength λ. When the interferometer is illuminated by a broadband source, some spectral components will experience maximum transmission, while others will be reflected by the beam splitter toward the source, and the remaining components will be partially transmitted and partially reflected. Therefore, the spectral irradiance exhibits an oscillating pattern with a varying period depending on the refractive index dispersion in the sample and air, as shown in Fig. 2. This rapidly varying irradiance can be easily evaluated by a spectrometer with sufficient resolution.

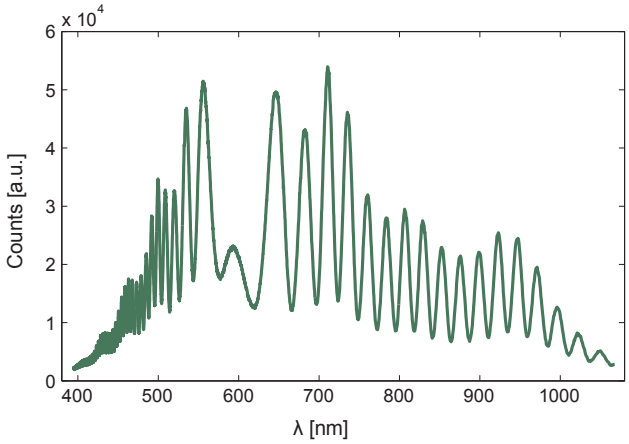


**Fig. 2.** Typical spectrogram obtained with SRWLI, showing a stationary phase point at a wavelength of ~590 nm.

### 2.1. Phase evaluation

To obtain information about the sample dispersion, the phase must be extracted from Eq. (1a). There are a variety of methods to accomplish this task, such as, the Hilbert, Fourier, and wavelet transforms, phase shifting methods, or phase calculation from minimum and maximum detection [23–26]. However, regardless of the method which is applied, and because the inverse trigonometric function is multivalued, we cannot extract the exact phase in Eq. (1) and only have access to its principal value defined in the interval $[-\pi, \pi]$. Thus, we must apply an unwrapping procedure to eliminate discontinuities; however, even in this case, the extracted phase, $\varphi_u$, differs from the correct one by a multiple of $2\pi$, which can be written as:

$$\varphi_u(\lambda) = 4\pi\,[d(n - n_{air}) - n_{air}\,l]/\lambda - 2k\pi, \quad k \in \mathbb{Z}. \tag{2}$$

Hence, to solve the equation for the refractive index, $n$, we must first calculate the value of $k$. Previously, there have been some attempts to overcome the phase ambiguity and obtain the value of $k$ [11,14,15]. However, we believe that any method has an inherent error, and the correct approach is to calculate the refractive index separately at a particular wavelength, $\lambda_0$. Given the value of the refractive index at this wavelength, $n_0$, $k$ is calculated using Eq. (2) as:

$$k = \text{nint}\{2[d(n_0 - n_{0air}) - n_{0air}\,l]/\lambda_0 - \varphi_u(\lambda_0)/2\pi\}, \tag{3}$$

where nint is the nearest integer function. By inserting $k$ into Eq. (2),