Optics and Lasers in Engineering 51 (2013) 533–537

Contents lists available at SciVerse ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng

Common-path spectral-domain optical low coherence interferometric system for the measurement of small changes in refractive index of Liquid Crystal cell

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ARTICLE INFO

Article history:
Received 1 August 2012
Received in revised form
15 November 2012
Accepted 30 November 2012
Available online 17 January 2013

Keywords:
Spectral-domain OCT
Interferometry
Liquid crystal
Refractive index
Hilbert transform

ABSTRACT

We report the measurement of small changes in the refractive index of liquid crystal (LC) with applied voltage using a common-path spectral-domain optical low coherence interferometric system. Changes in the spectral modulations were observed as a function of voltage applied to the LC cell in steps. Hilbert transform fringe analysis was used for the extraction of the phase of the spectral interference fringe signal. The change in the refractive index of the LC material as a function of voltage was then determined from the phase information. The present system is common-path, yields a higher stability in measurement and compensates the optical length perturbation and hence can be used in real time.

1. Introduction

Optical coherence tomography (OCT) is a non-contact, non-destructive technique for high resolution cross-sectional imaging of microstructures in biological tissues and industrial objects in real-time [1–4]. OCT can be broadly classified into two categories, i.e., time-domain OCT (TD-OCT) and frequency-domain OCT (FD-OCT) [1]. FD-OCT has been a more powerful technique in terms of speed and sensitivity and is implemented in two modes, i.e., spectral-domain OCT (SD-OCT) and swept-source OCT (SS-OCT) [1–6]. In SD-OCT, the interference signal is detected by a spectrometer using a high-speed multi-element linear CCD or photodiode array detector. The delay and magnitude of the optical reflections from the sample can be detected by Fourier transforming the spectral interference signal. SD-OCT technique can be used for measuring the refractive index (RI) of a sample by analyzing its spectral intensity as a function of wavelength. Reflections from all the interfaces in the sample interfere with the light reflected from the reference mirror to produce the modulations in the detected spectrum with periods corresponding to the optical path length difference with respect to [5]. In TD-OCT precise phase measurement is difficult due to the considerable phase jitter induced by vibration and noise generated due to the mechanical scanning involved in the reference arm. On the other hand, in SD-OCT the mechanical scanning of reference arm is not required so phase stability is higher [7–9] as compared to TD-OCT. Therefore, using SD-OCT one can extract both conventional OCT image and the phase information from the spectral interference fringe signal. The phase information can further be utilized for the determination of RI of the objects under investigations. The SD-OCT has been used for various applications in biology and industrial objects for the simultaneous tomographic imaging and RI measurement [8–11].

The importance of liquid-crystals (LC) has increased tremendously in various engineering and industrial applications. Liquid crystal display (LCD) devices are widely used for our day to day life and many liquid crystal optical devices are also used for various purposes such as display devices, machine vision displays, telecommunication, material science, data storage, measurement equipment, military systems, energy-related applications, optical and engineering science, medicine and biology, photonic liquid crystal, phase modulation of light for optical computing, laser beam shaping digital holography, diffractive optics etc. [12–14].

The electro-optical characteristics of LC material, such as, guest–host effect, bi-stability and field-induced director axes re-orientation and switch-on voltage, are important factors, for the display application [15]. LC is a birefringence material, and has two RI one parallel (extraordinary RI) and other perpendicular (ordinary RI) to the director of LC material. The difference of these two RIs is the birefringence of the LC material which is in the range of 0.1–0.5. Initially, in the absence of electric field applied to LC cell, all the molecules are parallel to the alignment layer on the

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http://dx.doi.org/10.1016/j.optlaseng.2012.11.017

glass plate i.e., in X–Y plane as shown in the inset of Fig. 1. The electric field associated with light passing through the LC cell in the direction of the *Z*-axis is parallel to the glass surface of the cell and sees the extraordinary RI of LC material. When external DC electric field is applied to the LC cell, then LC molecules, corresponding to the active area of the cell, start to rotate in the direction of applied electric field and finally become perpendicular (along *Z*-direction) to the glass surface of the cell. Thus in this condition electric field associated with light passing through the LC cell is parallel to the glass surface of the cell and sees the ordinary RI of LC material [16]. Thus if we apply the electric field to the cell then for light passing through the cell, the RI changes to ordinary RI from extraordinary RI and hence optical path length changes accordingly.

Therefore, there is an important requirement to measure the small change in RI of LC as the applied voltage changes. Spectral-domain optical low coherence interferometry (SD-OLCI) can be a potential technique for determining such small changes in RI and optical path length in situ over a wide range of wavelengths. In this paper we use the common-path SD-OLCI system for the measurement of variation of RI of the LC material as a function of voltage applied to the cell. Since an LC cell consists of a multilayer structure, using coherent light source like laser having long temporal coherence length will cause multiple reflections from each layer and will produce multiple interference patterns resulting in cross talk. To avoid this cross-talk we have used a low coherence light source so that the interference occurs only between the light reflected from upper surface and bottom surface of the LC cell cavity. On applying the voltage to the cell, the LC molecules orient resulting in small change in the RI of the cell. This change in RI leads to a small change in the optical path length resulting in a minute change in the spectral modulations of the SD-OLCI signals. Hilbert transform fringe analysis was used for the extraction of the phase of the spectral interference fringe signal. In a common-path SD-OLCI system both reference and sample arms share nearly the same path. Hence the experimental set-up is much simpler, low cost and has the ability to choose interchangeable probes as well as the freedom to use any arbitrary probe arm length. For a common-path OCT system, the reference and sample signals share the same path so that the reference offset can be changed directly by adjusting the distance between the fiber probe and the sample surface. Moreover, it does not have the problem of polarization and dispersion mismatch. Especially, as mentioned, due to the numerous distinctive features described above, a common-path OCT system has great potential for many applications not only in terms of efficient functional (blood flow/neuron activation/oxymetry) and morphological (structural) biological sample imaging but also in surgical applications such as micro-retinal and neurological surgeries [17–22]. But the change in RI of LC cell as a function of applied voltage has not been studied by SD-OLCI so far to the best of the author's knowledge.

2. Principle of spectral-domain optical low coherence interferometry

The schematic of SD-OLCI is shown in Fig. 1. In SD-OLCI the interference signal between the light reflected from the reference mirror and backscattered from the sample recorded by spectrometer can be expressed as follows [23–25]:

$$I(k) = I_R + I_O + 2[I_R I_O]^{1/2}\,\mathrm{Cos}[2k\Delta d] \tag{1}$$

where I_R and I_O are the reference and object irradiance distributions respectively, k is wavenumber $k = 2\pi/\lambda$ with λ being the wavelength of light and Δd denotes OPD between sample and reference arms. To extract the phase the spectral interferogram is Fourier transformed, and spatially high-pass filtered to isolate the sinusoidal term and eliminate the background components. The filtered sinusoidal term can be expressed as

$$S(k) = 2[I_R I_O]^{1/2}\,\mathrm{Cos}[2k\Delta d] \tag{2}$$

The complex analytical signal associated with the real function of $S(k)$ can be obtained as follows:

$$Z(k) = 1/2[S(k) + j\{Hilbert(S(k))\}] \tag{3}$$

In Eq. (3) the imaginary part of the right-hand side stands for a principal-value integral, easily identifiable as the Hilbert transform of $S(k)$. Using Eq. (3) the wrapped phase associated with complex analytical signal $Z(k)$ is calculated as

$$\phi(k) = \tan^{-1}\left\{\frac{Im[Z(k)]}{Re[Z(k)]}\right\} \tag{4}$$

Note that $Z(k)$ exhibits rapid phase modulations; $\phi(k)$ is strongly wrapped and varies between $-\pi$ and $+\pi$. The absolute phase is recovered by unwrapping the calculated phase as discussed in Refs. [18,19]. The unwrapped phase of a sinusoidal function $Z(k)$ varies linearly with wavenumber k. In the active area of the cell the LC molecules rotate with applied-field and hence the RI along *Z*-direction changes in the active area of the cell with respect to the rest of the area. Due to this change in RI the spectrum starts shifting. So there will be a change in the phase of spectral

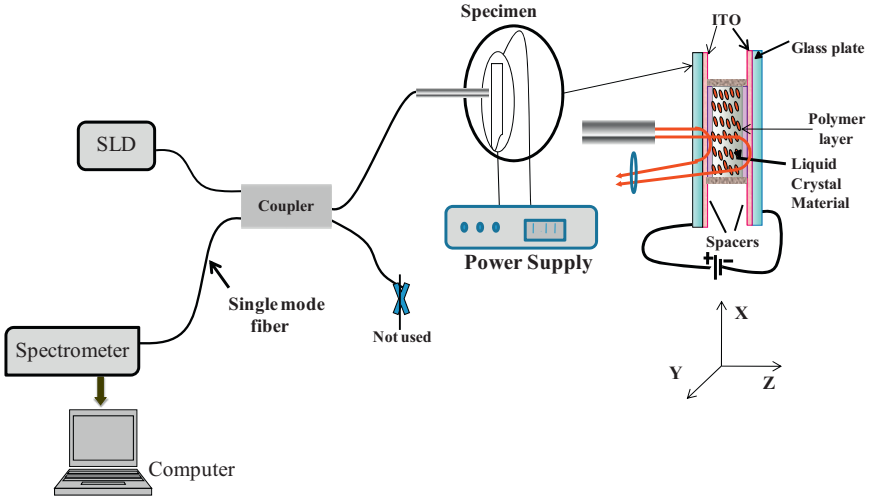

Fig. 1. Schematic diagram of common-path SD-OLCI system.