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OCT imaging with temporal dispersion induced intense and short coherence laser source

Suman K. Manna [a,b], Stephen le Gall [b], Guoqiang Li [a,c,*]

[a] Department of Ophthalmology and Vision Science, The Ohio State University, 1330 Kinnear Road, Columbus, OH 43212, USA
[b] Department of Optics, Telecom Bretagne, 655 Avenue du Technopole, Plouzané 29200, France
[c] Department of Electrical and Computer Engineering, The Ohio State University, Columbus, OH 43212, USA

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ABSTRACT

Lower coherence length and higher intensity are two indispensable requirements on the light source for high resolution and large penetration depth OCT imaging. While tremendous interest is being paid on engineering various laser sources to enlarge their bandwidth and hence lowering the coherence length, here we demonstrate another approach by employing strong temporal dispersion onto the existing laser source. Cholesteric liquid crystal (CLC) cells with suitable dispersive slope at the edge of 1-D organic photonic band gap have been designed to provide maximum reduction in coherence volume while maintaining the intensity higher than 50%. As an example, the coherence length of a multimode He–Ne laser is reduced by more than 730 times.

1. Introduction

Optical coherence tomography (OCT) is a rapidly developing imaging modality, which provides non-invasive cross-sectional images through weakly scattering, semitransparent biological and non-biological media with micrometer-scale resolution [1–4]. Currently, there are three important criteria in typical OCT measurements: the maximum depth of imaging, the speed of measurement, and the speckle appearance in imaging. In general, under the laser safety limit, use of an intense laser source enables high penetration depth of imaging through a scattering or absorptive media and improves the signal to noise ratio (SNR) of the OCT imaging. But, one of the signature properties possessed in a conventional laser source is the larger coherence volume [5–9], which has disadvantages in promotion of speckles. The speckle is generated when an imaging sample imparts a range of random path length differences over a highly coherent optical source. Therefore, in order to circumvent the problem of the speckle appearance, the coherence volume of a laser source has to be reduced. Although reduction in spatial coherence of the laser effectively reduces the coherence volume, while we are talking about OCT, the temporal coherence length of the laser source has to be very low indeed, because, standard OCT images are synthesized from low (temporal-) coherence interferometry (LCI) and the signals are obtained by the so-called depth-or A-scan. The complex degree of the temporal-coherence defines longitudinal or depth point spread function, whose full width at half maximum (FWHM) defines the depth resolution in OCT [3]. For Gaussian light, the depth resolution is

$$\Delta z=\frac{c\tau_c}{2}=\frac{2\ ln\ 2}{\pi}\frac{\lambda_0{}^2}{\Delta\lambda}=\frac{l_c}{2}\ldots \tag{1}$$

where τ_c is the FWHM coherence time, l_c is the FWHM coherence length, λ_0 is the center wavelength, and $\Delta\lambda$ is the spectral bandwidth. From Eq. (1), it is clear that the higher depth resolution in OCT demands larger bandwidth or lower temporal coherence of the light source.

There is an intensive research going on engineering the larger bandwidth as well as higher intensity for the laser source [10–13]. First implementations of the OCT principle used superluminescent laser diodes (SLDs) at $\lambda_0=830nm$. These diodes yield coherence lengths in the order of 10-μm range but, strive with the lower beam power in 10 mW range. Clivaz et al. [3], used the fluorescence light from a Ti-sapphire crystal pumped by an argon laser operating at the central wavelength of $\lambda_0=780nm$ and a beam power of 4.8 μW has been obtained with a depth resolution of 1.9 μm. Schmitt et al. [5] used two light emitting diodes at peak wavelengths of 1240 nm and 1300 nm to synthesize a source with a short coherence length. However, along with the progress in different synthetic engineering techniques towards the reduction

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[*] Corresponding author at: Department of Ophthalmology and Vision Science, The Ohio State University, 1330 Kinnear Road, Columbus, OH 43212, USA.
E-mail address: li.3090@osu.edu (G. Li).

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of the coherent length, it could be an interesting approach to reduce it further by employing an additional highly temporal dispersive medium. In our previous work [14], we have shown the strong temporal dispersion of the photonic bandgap available in a CLC. Depending on the thickness (L) of the dispersive medium, the coherence length (l_c) of the multimode He-Ne laser source has been shown (in our previous work) to be reduced from 22 cm to 5 cm, hence the effective coherence volume gets reduced and facilitates to have speckle free high throughput image of a biological sample [14]. In this communication, our prime objective is to illustrate another extension of our temporal dispersive medium to further reduce the value of l_c of the same source to 300 μm and demonstrate a series of OCT images. We believe that this easily employable additional dispersive medium can reduce the l_c value beyond the intrinsic value of l_c of any source. This generic approach could be interesting for the OCT field.

2. Analytical treatment

To analyze the impact of the temporal dispersion D on the coherence volume, we assume that the spectral distribution function $s(\omega)$ of the light source is of Gaussian type profile:

$$S(\omega)=\exp\left[-\frac{(\omega-\omega_0)^2}{2(\Delta\omega)^2}\right]/(2\pi)^{1/2}\Delta\omega\ldots \tag{2}$$

where ω is the angular frequency, ω_0 the center angular frequency of the distribution function$S(\omega)$, and $\Delta\omega$ the spectral width. Under the assumption of the spectral distribution profile $S(\omega)$, the degree of coherence $|\gamma|$ is derived as follows [15,16]:

$$|\gamma|=\frac{1}{b^{1/4}}\,exp\left[\frac{-4\pi^2\left(\Delta\lambda/\lambda^2\right)^2(2d)^2}{b}\right]\ldots \tag{3}$$

with

$$b=1+\left(\frac{\Delta\lambda}{\lambda}\right)^4(2\pi cDL)^2,\ \ldots. \tag{4}$$

where c is the velocity of light in free space, $2d$ is the optical path difference between the two arms of the interferometer, and $\Delta\lambda$ is the spectral width, λ is the center wavelength, L is the thickness of the dispersive medium. It is clear from Eqs. (2) and (3) that the absolute value of the degree of coherence degrades as L and D become larger. Usually a two-beam interferometer is used in OCT. The output of a low coherence light source is split into a probe beam which is directed towards the sample and a reference beam which is directed towards the retro-reflecting reference mirror of the interferometer. Wave groups remitted and/or reflected from both the sample and the reference mirror are recombined at the beam splitter and propagated to a photo detector. The interference term at the exit of an empty interferometer (without sample) can be analytically expressed by the autocorrelation of the two corresponding beams of complex amplitude E at time t and $t+\tau$, where τ is the delay between the two beams. The autocorrelation function is written as

$$G(\tau)=Re\left\{\langle E(t+\tau)E^{*}(t)\rangle\right\}\ldots \tag{5}$$

This $G(\tau)$ can be called as impulse response function of the empty interferometer. Note that, if the delay $\tau\le\tau_c$, only at that condition interference appears. If we introduce our dispersive medium CLC at one of the two arms of the interferometer, the frequency and length-dependent phase dispersion $\varphi_{disp}(\omega;L)$ of the complex amplitude at that arm can be written as [15–17]:

$$\varphi(\omega;L)=exp\left[i\varphi_{disp}(\omega;L)\right]\ldots \tag{6}$$

with $\varphi_{disp}(\omega;L)=(2\pi/\lambda)L[n(\omega)-1]$, where $n(\omega)$ is the average. refractive index and L is the thickness of the CLC medium. With the increase of the thickness of the medium, more dispersion is introduced in phase $\varphi(\omega;L)$ and hence the degree of coherence volume ($l_c\times\lambda^2$) of the probe beam is reduced by a factor of γ as in Eq. (3). As the temporal coherence length l_c and hence τ_c is reduced, the time width (τ) of the autocorrelation function $G(\tau)$ becomes shorter. As a result the depth resolution is enhanced further by a factor γ in OCT imaging even using the same source.

3. CLC as 1-D photonic crystal

CLC possesses a supra-molecular helical periodic structure (Fig. 1(a)) of periodicity P, which is related with the optical wavelength λ by the following relationship [18]:

$$\lambda = n_{avg}.P\ldots \tag{7a}$$

$$\Delta\lambda = \Delta n.\ P\ldots \tag{7b}$$

where n_{avg} is the average refractive index and Δn is the birefringence of the liquid crystal molecule. Because of this unique optical property of the CLC, incoming light of wavelength λ senses the helical periodicity parallel to the helix axis inside the CLC

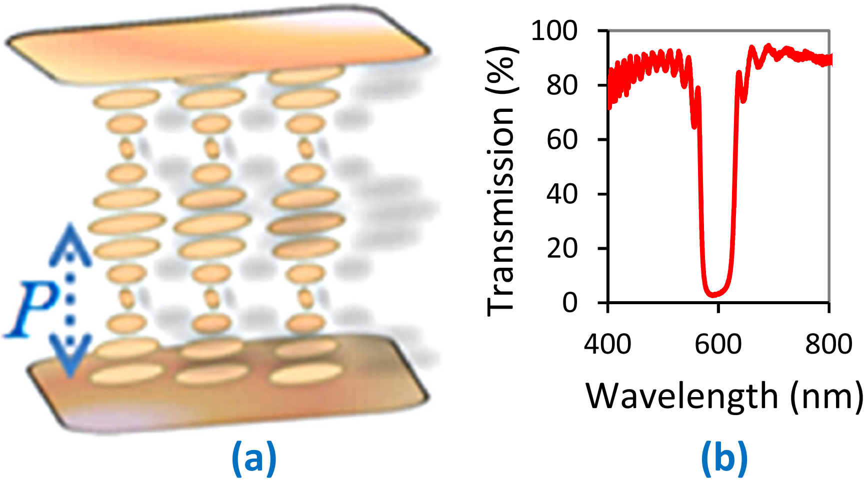

Fig. 1. (a) Periodic arrangement of the CLC molecular system. (b) Transmission spectrum of the 4 μm-thick CLC cell doped with R.H and L.H. chiral dopants.