Transmission Optical Coherence Tomography Based Measurement of Optical Material Properties

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We demonstrate that Fourier-domain transmission OCT is a versatile tool to measure optical material properties of turbid media. Based on an analytical expression for the transmission OCT signal we can determine the group refractive index, group velocity dispersion, absorption coefficient, and scattering coefficient. The dispersion is accurately measured for water/glucose mixtures. The optical attenuation is accurately measured in the spatial domain based on Mie calculations combined with concentration dependent scattering effects. In the wavevector domain the spectral dependence of the optical attenuation is accurately measured. The developed technique can be used for optical sensing and optical tomography.

Introduction

Optical material properties are not only important in the field of optics, but also in other fields such as pharmaceuticals, medical diagnostics, photodynamic therapy and food production. In many of these fields the optical materials are turbid, i.e., they have both optical absorption and scattering. Therefore, characterisation of the optical properties in turbid media is often challenging.
Optical properties such as refractive index and optical attenuation can be measured using various techniques. Optical attenuation, for example, can be measured using collimated transmission measurements [1]. The refractive index can be determined using confocal microscopy [2]. Many techniques for measuring of optical material properties provide either the refractive index or the attenuation coefficients. Additionally, some techniques suffer from light scattering in the sample, while others rely on it, causing restrictions in sample size and the type of sample.
Here we present the use of transmission OCT to determine the optical properties of turbid media. Transmission OCT was first used by Hee et al. [3] for imaging of objects embedded in turbid media. Recently, transmission OCT has been used to measure the scattering coefficient in turbid media [4]. In this work Fourier-domain transmission OCT is used to determine the group refractive index, the group velocity dispersion (GVD) as well as the (spectrally resolved) optical attenuation coefficients.

Methods

Fourier-domain transmission OCT is based on a Mach-Zehnder interferometer, as shown in figure 1. We use low-coherent light from a superluminescent diode with a center wavelength of 1300 nm and a spectral bandwidth of 110 nm. Light interacts with with a sample in one of the arms of the interferometer. After recombination, the interference pattern is recorded in the spectral domain using a home build spectrometer. The interference spectrum resulting from a homogeneous object with thickness L is given by

$$I_{int}(k) = 2\alpha(1-\alpha)E_s^2(k)\exp\left(-\frac{1}{2}L\mu_t(k)\right)\cos[kL(n(k)-1)]. \tag{1}$$

Sample properties can be determined in the spectral domain from the complex signal obtained from the Hilbert transform

$$\widetilde{I_{int}}(k) = I_{int}(k) + i\mathscr{H}\{I_{int}(k)\}. \tag{2}$$

The group refractive index, n_g, and the GVD can be calculated from the unwrapped phase of the complex signal using a polynomial fit. After a dispersion correction [5] the optical attenuation coefficient, μ_t, can be determined in both the spectral an spatial domain. In the spectral domain, the optical attenuation coefficient, μ_t can be calculated from the magnitude of the complex interference signal using

$$\mu_t = L^{-1}\ln\left(\frac{|\widetilde{I_{ref}}(k)|^2}{|\widetilde{I_{sam}}(k)|^2}\right), \tag{3}$$

with $\widetilde{I_{sam}}(k)$ and $\widetilde{I_{ref}}(k)$ the complex interference signals measured with and without sample respectively. Taking the inverse Fourier transform of Eq. 1 we obtain an optical path length distribution, containing two peaks with a heigh proportional to the optical power transmitted trough the sample. Application of Eq. 3, where $\widetilde{I_{sam}}(k)$ and $\widetilde{I_{ref}}(k)$ now represent the heights of the signal peaks in the spatial domain for a sample and reference measurement yields the attenuation coefficient.

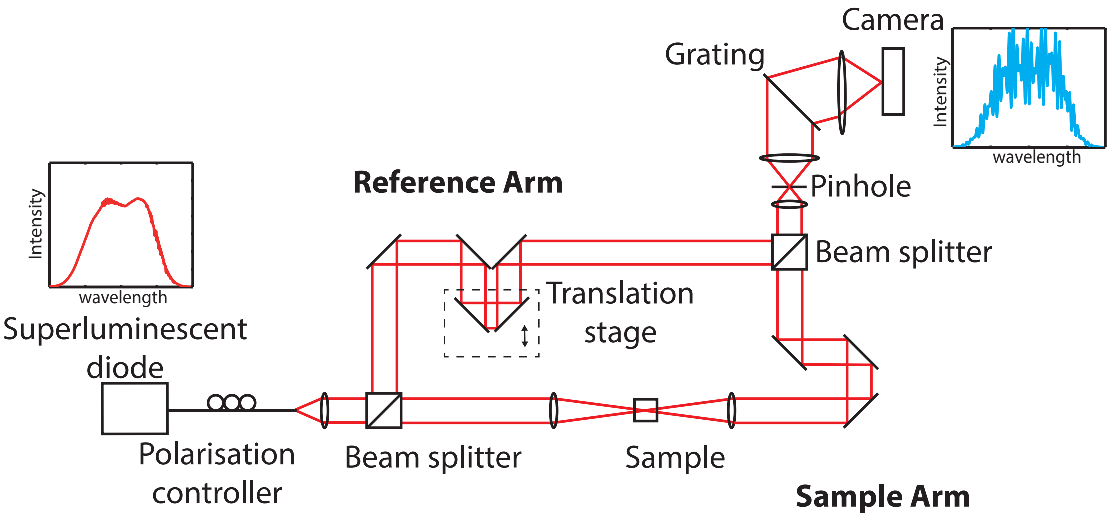

Figure 1: Schematic diagram of the experimental setup.

Results

The group refractive index and the GVD have been determined for aqueous glucose solutions of different volume fractions, shown in Fig. 2. From a linear fit the bulk optical

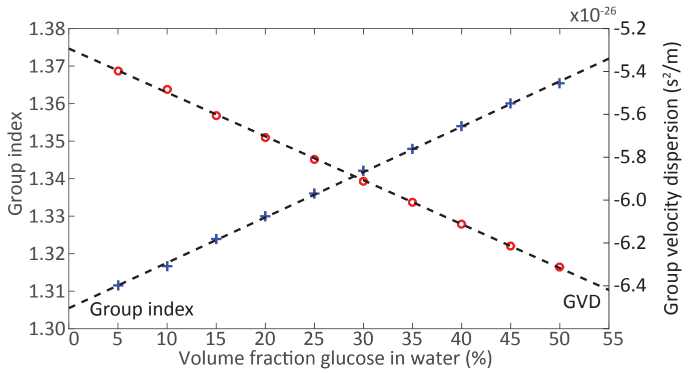

Figure 2: Measured group refractive index and GVD for glucose-water solutions.

properties for pure glucose can be estimated. In this way, we obtain a group refractive index of 1.465 ± 0.004 and a GVD of $(-6.4 \pm 0.03)10^{-26}$ s^2/m.
The group refractive index also has been determined for various suspensions of 0.5 µm silica particles, as shown in figure 4(a). A linear fit gives us a refractive index for bulk silica of 1.46 ± 0.02. In addition, the attenuation coefficient for suspensions of 0.5 µm and 1.5 µm silica particles have been measured for various volume fractions. The data is corrected for the water absorption, leaving the scattering coefficient caused by the silica particles. Figure 4 (b) shows the scattering coefficient for the suspensions as function of the volume fraction of particles. Data is compared to Mie calculations and fitted with a dependent scattering model [4]. The input of the model is the refractive index of the medium and the particles, the wavelength, the experimentally determined particle size and the volume fraction. Setting the particle refractive index as the free parameter for the fitting we obtain $n_0 = 1.430 \pm 0.009$ for the 0.5 µm particles, and $n_0 = 1.444 \pm 0.005$ for the 1.5 µm particles.

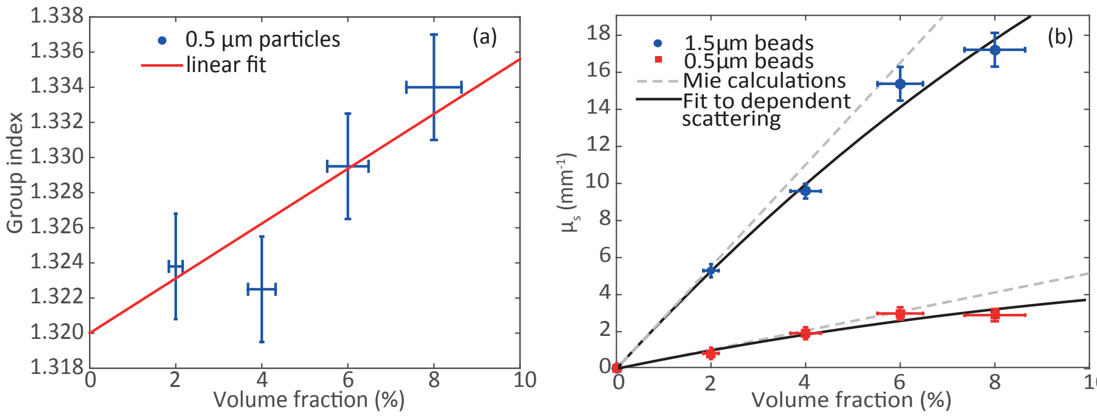

Figure 3: (a) Group refractive index for 0.5 µm particles as function of the volume fraction (blue), linear fit to the data (red, solid). (b) The scattering coefficent as function of the volume concentration of particles. Measurement are compared to Mie calculations (gray, dashed) and fitted with a dependent scattering model (black, solid).

The spectrally resolved attenuation spectra are measured for water (Fig. 4(a)) and the 2 vol.% 1.5 µm silica particles (Fig. 4(b)). The results agree well with literature (water) and dependent scattering calculations (silica suspensions). However, on the edges of the spectra some deviations occur. These deviations are caused by the low illumination intensities at these frequencies and becomes more severe for highly scattering samples. Hence this method is only suitable for samples with a thickness up to 10 mean free path lengths.

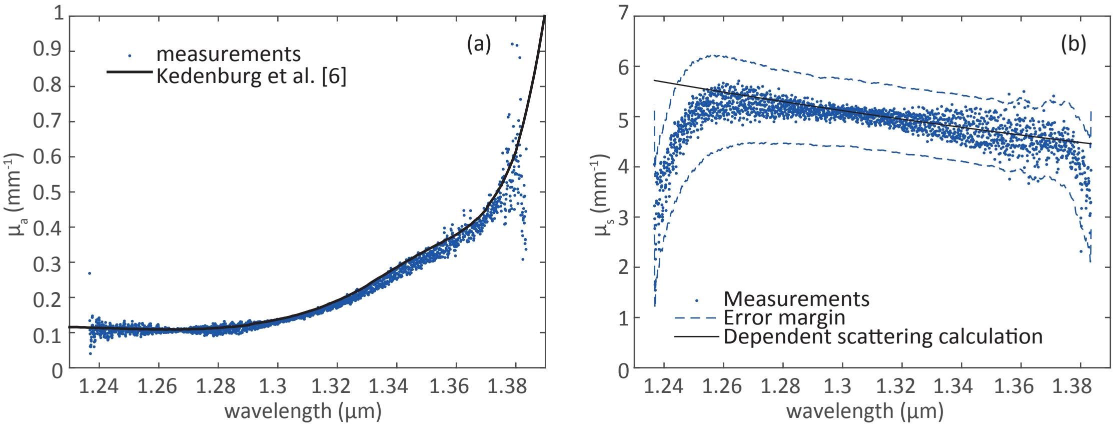

Figure 4: (a) Measured absorption spectrum of water (blue, dots) and its comparison to literature [6] (black, solid). (b) Measured scattering spectrum for 2 vol.% 1.5 μm silica particles (blue, dots) compared to dependent scattering calculations (black, solid). Error margin is denoted by the dashed lines.

Conclusion

In conclusion, we presented Fourier-domain transmission OCT as a method for measurement of the group refractive index, the group velocity dispersion and the (spectrally resolved) attenuation coefficient. The proposed methods are validated using several experiments. We showed that transmission OCT is a powerful and flexible tool for the measurement of various optical properties. Possible applications include OCT imaging, microfluidics, lab-on-a-chip technology and optical tomography.

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