Ambiguity of optical coherence tomography measurements due to rough surface scattering

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Abstract: Optical coherence tomography (OCT) images are frequently interpreted in terms of layers (for example, of tissue) with the boundary defined by a change in refractive index. Real boundaries are rough compared with the wavelength of light, and in this paper we show that this roughness has to be taken into account in interpreting the images. We give an example of the same OCT image obtained from two quite different objects, one smooth compared to the optical wavelength, and the other rough.

OCIS codes: (110.4500) Optical coherence tomography; (240.5770) Scattering, rough surfaces.

References and links

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1. Introduction

Optical coherence tomography (OCT) is a non-invasive three-dimensional imaging technique capable of producing high-resolution images through inhomogeneous samples [1–5]. This technique is of great utility, in particular, in biomedical applications for imaging layered objects like, for example, the retina [6]. In principle, OCT enables the retrieval of the physical parameters of each layer of a sample (for example, thickness and refractive index) from rather simple optical measurements. However, the retrieval of quantitative data about a sample is complicated due to the various scattering mechanisms. In practice, the parameters of layers are estimated from OCT images, but layers are only qualitatively differentiated by the intensity of the OCT signal, which depends not only on the thicknesses and refractive indices but on the strength of scattering as well. Clinically, the empirical approach is to compare OCT images to histology, rather than attempt the difficult task of solving an inverse problem [5].

The principle of time-domain OCT is that light scattered by an object is interfered with a reference beam: constructive interference occurs when the optical paths for the scattered object beam and reference beam are the same to within the longitudinal coherence length of the light source. For the purposes of interpreting the final image, we can distinguish three sources of reflection and scattering from an arbitrary object: (i) Fresnel reflection from plane interfaces of differing refractive index, (ii) scattering due to the turbid or diffuse nature of the sample, and (iii) scattering from the rough interface between layers in the object. The Fresnel reflection contribution is very dominant in certain samples, for example when imaging the cornea and lens of the eye in anterior chamber OCT. Indeed, the interpretation of the OCT image is similar to that of a radar return, with clear "reflections" from surfaces of differing refractive index. In many other examples of OCT imaging in tissue, the turbid nature of the sample is the main contributor to the OCT signal, and many studies of this have been carried, largely using numerical Monte Carlo techniques [for example 7,8]. It should be noted that the polarization state of the scattered light must be considered in this case.

The third contributor to the OCT signal, the light scattered due to the roughness of the interface between two media of differing index, has not been considered in the literature. In this paper, we show that this contribution is important for a layered sample and can affect dramatically the algorithm of the solution of the inverse problem: retrieval of the geometrical and optical parameters of the sample from the OCT interferogram. We show, as an example, that the *same* interferogram can be obtained with two quite different samples, one with where the surfaces are smooth (and therefore only the Fresnel reflection term (i) is considered) and the other where the surfaces are rough.

In a simple time-domain implementation of OCT, the algorithm of the retrieval depends on the fact that the constructive interference of the fields multiply scattered at the interlayer boundaries manifests itself as peaks in the dependence of the measured intensity on the position of the reference mirror. The problem is that OCT is based on the reflection from the layers of the sample and therefore is sensitive to the roughness of these layers. To the best of our knowledge, there is no reliable OCT algorithm that takes the multilayer surface scattering into account. Here we present an approximate method for the analytical study the reflection from samples consisting of rough layers with low dielectric contrasts, and use it to estimate the error introduced into the OCT algorithm if the surface scattering is neglected. For clarity, the analysis is carried in the time-domain using a scalar approach, but the same general conclusions will apply to Fourier-domain OCT and when polarization is considered, since the physical model is the same. Since in weakly scattering media the contributions from volume and surface scatterings are additive, in what follows we assume that all slabs comprising a sample are homogeneous dielectric layers.

This paper deals only with the forward (or 'direct') problem, that is, computing the OCT signal for given objects. In a practical situation, one has to serve an inverse problem, and the task-based approach of [5] should be used. It is, however, important to use the correct object model in the inverse problem, and we show the importance of including surface roughness (as well as volume scattering and Fresnel reflection) in that model.

2. OCT signal from multiple layers

The frequency (ω) component of the non-monochromatic wave normally incident on a layered sample (the layers are parallel to the (x, y) plane) is represented in the form

$$E_{in}(z,t;\omega) = s(\omega)e^{i(kz-\omega t)}, \tag{1}$$

where $s(\omega)$ is the frequency spectrum of the source and k is the wavenumber. In a standard OCT setup based on the Michelson interferometer, the detector measures the time-averaged intensity of the outgoing field integrated over the whole frequency spectrum of the signal [1].

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Under the assumption that the mirror and the 50:50 splitter are lossless, this intensity is proportional to (for derivation, see Ref [1].):

$$I(\Delta x) = \int_{-\infty}^{\infty} \left\{ \frac{1}{4} |s(\omega)|^2 \left[|H(\omega)|^2 + 1 \right] + \frac{1}{2} \Re \left\{ |s(\omega)|^2 H(\omega) e^{-i\Phi(\Delta x)} \right\} \right\} d\omega, \tag{2}$$

where

$$\Phi(\Delta x) = 2 \frac{\omega}{c} \Delta x, \tag{3}$$

is the phase shift due to the shift of the reference mirror by a distance Δx, and $H(\omega)$ is the sample response function, i.e. the complex monochromatic amplitude of the field, which presents the overall reflection from all layers distributed in z direction within the sample

$$H(\omega) = \int_0^L r(\omega, z) \exp\left(i2n(\omega, z)kz \right) dz, \tag{4}$$

Here $r(\omega,z)$ is a local reflection coefficient at the point z and L is the length of the sample.

To calculate $H(\omega)$ for a layered medium we consider the reflection of a monochromatic wave from a stack of N plane-parallel dielectric layers with different refractive indices, n_j, and thicknesses, z_j.

If the dielectric contrasts between two adjacent layers are small (low-contrast sample), so that

$$\eta \equiv \left| \varepsilon_j - \varepsilon_{j+1} \right| << \varepsilon_j, \varepsilon_{j+1},$$

the reflection coefficients at all interfaces are small, and one can take into account only single-reflected waves, i. e., to neglect the decrease of the field during its propagation before and after reflection from j^{th} interface. This approximation yields

$$\begin{aligned} H(\omega) &= \sum_{j=1}^{N} r_j (\omega, z_j) \exp\left(i \frac{2\omega}{c} Z_j \right); \\ Z_j &= \sum_{m=1}^{j} n_m z_m; \\ n_m &= \sqrt{\varepsilon_m}. \end{aligned} \tag{5}$$

To calculate the OCT interferogram for an N-layered sample, we assume for the sake of simplicity the rectangular shape of the frequency spectrum of the incident signal,

$$S(\omega) = \begin{cases} 1 & for \omega_1 \le \omega \le \omega_2 \\ 0 & for \omega \le \omega_1; \omega \ge \omega_2 \end{cases}, \tag{6}$$

After rather simple, but lengthy calculations, from Eqs. (2) – (5) we obtain

$$I_N(\Delta x) = C_N + F_N(\Delta x), \tag{7}$$

where C_N is independent of Δx, and

$$\begin{aligned} F_N(\Delta x) &= \sum_{j=1}^{N} r_j \frac{2 \cos \frac{2\Omega}{c} \left(Z_j + \Delta x \right) \sin \frac{2\omega}{c} \left(Z_j + \Delta x \right)}{Z_j + \Delta x}; \\ \Omega &= \omega_1 + \omega_2; \omega = \omega_1 - \omega_2. \end{aligned} \tag{7a}$$

#152106 - $15.00 USD Received 1 Aug 2011; revised 25 Sep 2011; accepted 25 Sep 2011; published 19 Oct 2011

Note that Eqs. (5) – (7) are rather general and are equally valid for both, ideal (flat) and rough layers, the difference residing only in the explicit form of the reflection coefficients r_j.

3. Reflection from rough interface between two layers with small dielectric contrast

Interaction of the incident radiation with the surface roughness gives rise to the scattering in a certain range of angles and therefore reduces (as compared to the flat interface) the intensity reflected in the specular direction. Neglect of this effect, i. e. the use of the algorithm based on the theory of reflection from flat interfaces, will give rise to an error in the estimated refractive index difference across the interface. To account for the effect of the surface roughness, one has to substitute in Eq. (7) the corresponding expression for the reflection coefficients of the normally reflected coherent field.

The most popular analytical methods for the study of rough surface scattering are the small perturbation, and small slope approximations [9]. The small parameters of these methods are σ/λ (σ is the RMS height of the roughness, λ is the wavelength of the incident radiation) and the slope of the surface, $\gamma \sim\sigma/l$, respectively (l is the characteristic horizontal scale of the roughness). In particular, in the recent publication [10], a general solution for the electromagnetic field scattered from a layered structure with an arbitrary number of rough interfaces has been developed in the single-scattering approximation, and the mean power density (scattering diagram) has been calculated explicitly. In principle, the specularly reflected coherent field can also be found using the general formulas of [10]. Alternatively, the reflection coefficient from multi-layered systems can be calculated applying the perturbation theory developed in [11], which employs the low dielectric contrast as a small parameter of the perturbation expansion, and does not require smallness of the roughness height.

To use the low-contrast approximation [11], we assume that random deviations of the surface from the plane (surface roughness) are described by a single-valued real statistically homogeneous Gaussian random process $\varsigma(x)$ with zero mean value and given correlation function:

$$\sigma^2 = \left\langle \zeta^2(x) \right\rangle \quad ,\left\langle \zeta(x)\zeta(x') \right\rangle = \sigma W\left(\left|x-x'\right|\right) \quad ,\left\langle \zeta(x) \right\rangle = 0 \tag{8}$$

In the framework of the statistical approach, the specular reflection is associated with the mean field and its wave function is calculated by averaging over the ensemble of random realizations $\varsigma(x)$ [8]. Using the perturbation method developed in [11], the following expression for the reflection coefficient of the coherent field reflected at normal incidence from a randomly rough interface between two semi-infinite media with low dielectric contrast ($\eta = |\varepsilon_1\text{-}\varepsilon_2| <<1$) can be obtained:

$$r_1 = \frac{\eta}{4\varepsilon_1} e^{-2\varepsilon_1\sigma^2 k^2}, \tag{9}$$

Formula (9) corresponds to the case when the radiation propagates from the medium with the dielectric constant ε_1 to the half–space with the dielectric constant ε_2.

At $\sigma=0$ (smooth surface), Eq. (9) coincides with the low-contrast limit of the Fresnel reflection coefficient. The important feature that distinguishes Eq. (9) is the dispersion, i. e. the dependence of the reflectivity of the rough surface on the wavelength of the incident radiation.

To demonstrate the effect of the surface scattering on the accuracy of the retrieval the dielectric constant of a medium from reflectivity measurements we first consider the specular reflection from a rough vacuum – dielectric (with n = 1.02) interface. Obviously, to retrieve correctly the refractive index from the given (measured) value of the reflectivity r, Eq. (9) should be used. Figure (1) shows the rms-dependence of the relative difference (error) $\alpha = (n$-

#152106 - $15.00 USD Received 1 Aug 2011; revised 25 Sep 2011; accepted 25 Sep 2011; published 19 Oct 2011

$n_0)/n$, between the real value n = 1.02 (obtained from Eq. (9) at the wavelength λ = 800nm) and that (n_0) obtained by using the Fresnel reflection coefficient $r_F = (n_0-1)/(n_0+1)$.

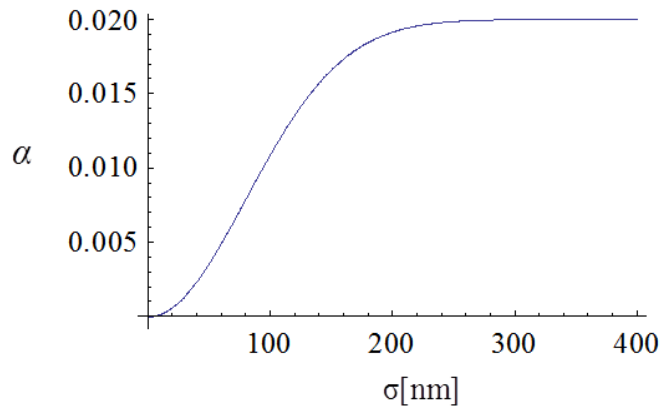

Fig. 1. Roughness-induced relative error in the refractive index retrieved from the reflection coefficient of the dielectric half-space with n=1.02

It is clear that roughness as small as σ ~λ/3 already leads to an error in the retrieved value of n of the same order as the index mismatch (n-1), i.e. makes the interface practically "invisible" in the specular direction. This is because the roughness scatters most of the radiation from normal to all other directions.

4. Numerical results

In this Section, the effect of surface scattering on the efficiency of the OCT of multilayered media is demonstrated by numerical simulations of interferograms for a four-component system shown in Fig. 2.

First we estimated the accuracy of the single-scattering approximation Eq. (5). The comparison of the total reflected intensity calculated with the sample response function $H(\omega)$from (5) with that found by direct T-matrix numerical simulations shows that for the four-layered systems under consideration, the difference between exact and approximate values never exceeds 0.01%.

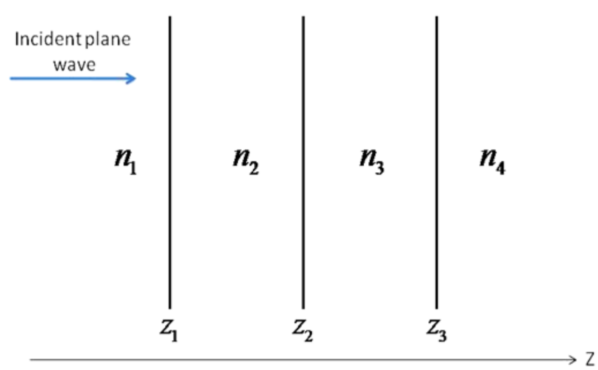

Fig. 2. Physical sample studied.

Presented in Fig. 3 is the OCT interferogram, Eq. (7), of the smooth (σ = 0) system with the following parameters: $n_1 = n_3 = 1.3$, $n_2 = n_4 = 1.31$; $z_1 = z_2 = z_3 = 15\mu m$; $\omega_1 = 2.28\times10^{15}$Hz, $\omega_2 = 2.43\times10^{15}$Hz.

#152106 - $15.00 USD Received 1 Aug 2011; revised 25 Sep 2011; accepted 25 Sep 2011; published 19 Oct 2011

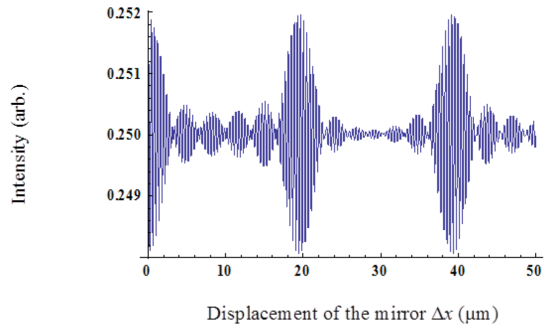

Fig. 3. OCT interferogram for the system shown in Fig. 2 with the parameters $\varepsilon_1 = \varepsilon_3 = 1.3$, $\varepsilon_2 = \varepsilon_4 = 1.31$; $z_1 = z_2 = z_3 = 15\mu m$; $\omega_1 = 2.28\times10^{15}Hz$, $\omega_2 = 2.43\times10^{15}Hz$.

It is clear that the position of each of three high maxima in Fig. 3 is connected to the thickness of j-th layer z_j as

$$\Delta x_j = n_j z_j$$
$$j = 1, 2, 3,$$

which enables one to find the product $n_i z_i$ for each layer. To account for the effect of the surface roughness, one has to substitute in Eq. (7) the reflection coefficient given by Eq (9).

Drawn in Fig. 4 are the OCT interferograms of the samples with the same parameters as in Fig. 3 but with rough interfaces z_1, z_2, z_3 (in Fig. 4 (a), $\sigma_1 = \sigma_2 = \sigma_3 = 0.1\lambda$; in Fig. (4b), (b) $\sigma_1 = \sigma_2 = \sigma_3 = 0.12\lambda$). The effect of the surface scattering is dramatic: roughness with rms 0.12λ causes ~20 times decrease in the peak amplitudes.

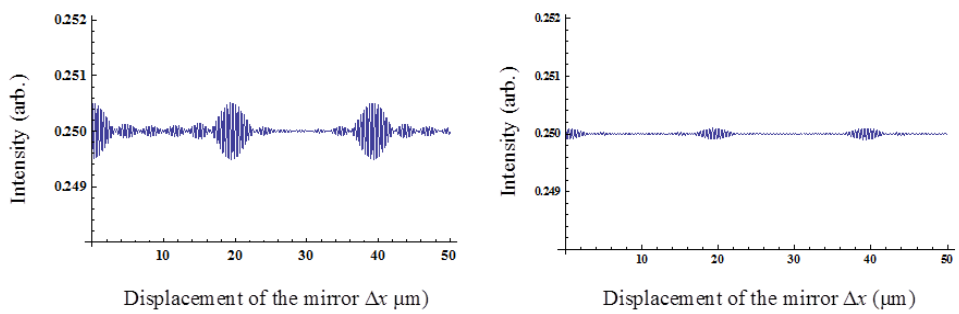

Fig. 4. OCT interferogram for the system with the parameters presented in Fig. 3 and rough interfaces z_1, z_2, z_3 with the rms: (a) $\sigma_1 = \sigma_2 = \sigma_3 = 0.1\lambda$; (b) $\sigma_1 = \sigma_2 = \sigma_3 = 0.12\lambda$ respectively.

Another example of how misleading the effect of the roughness on the OCT algorithm could be is presented below. Two different layered samples, one smooth (all $\sigma_j = 0$) with $n_1 = n_3 = 1.3$, $n_2 = n_4 = 1.31$ and thicknesses $z_1 = z_2 = z_3 = 15\mu m$; and another rough ($\sigma_1 = \sigma_2 = \sigma_3 = 0.13\lambda$) with different set of refractive indices ($n_1 = n_3 = 1.3$, $n_2 = n_4 = 1.4$) specially chosen to compensate for the effect of surface scattering have produced the same diagram shown in Fig. 5.

#152106 - $15.00 USD Received 1 Aug 2011; revised 25 Sep 2011; accepted 25 Sep 2011; published 19 Oct 2011

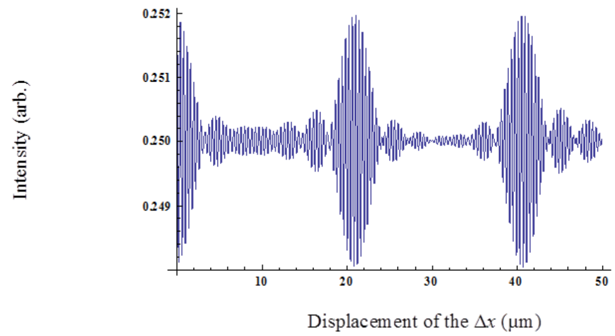

Fig. 5. Two interferograms (indistinguishable in Figure) from two different layered objects, one with smooth surfaces and the other with optically rough surfaces (see text for parameters of samples).

4. Discussion

We have shown that the same OCT signal can be obtained from two samples with differing refractive index of each layer, one with smooth interfaces (the case usually assumed, see, for example [5]) and the other with rough interfaces. This means that the interpretation of the OCT signal is ambiguous, and numerical values, for example of the refractive indices of each layer, cannot be determined without prior knowledge of the interface roughness. A real OCT signal from many layers contains scattering contributions from the turbidity, as well as the interfaces. For clarity we considered only the simplest case, where the turbidity is small (as in the anterior chamber of the eye), but we believe a more thorough study that included turbidity would reveal even greater ambiguity of OCT images.

We restricted our analysis to the very simplest case in which we study the interferogram formed in time-domain OCT, but the model used could equally well be applied in Fourier-domain OCT, obviously with the same results (since the physics remains the same). We also only considered the forward problem, whereas the real problem ultimately to be solved is an inverse one.

Almost all applications of OCT end up using qualitative, empirical image interpretation, in medical applications by comparisons with histology. Indeed the physical parameters that can be extracted are the dimensions and refractive indices of structures. The task of extracting other physical parameters, such as scattering coefficients, surface roughness parameters, etc. from OCT remains a significant challenge.

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