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Accurate phase estimation of vibrating interfaces using spectral estimation optical coherence tomography

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Abstract: Phase sensitive optical coherence tomography (OCT) is able to measure small axial motion at the level of ten nanometer. However, when interfaces are located close to each other, the phase of one interface may influence the phase of the other interface. This spectral leakage hampers the ability to see relative motion between structures within the sample, especially when the separation is below the axial resolution. Spectral estimation OCT (SE-OCT) based on IAA can not only improve the axial resolution beyond the conventional bandwidth limitation, but also reduce this spectral leakage. Here we show accurate reconstruction of the vibration of an interface at sub-resolution distance from a high-intensity interface with a different vibration frequency. Phase preserved IAA successfully reduces spectral leakage and outperforms conventional DFT-based reconstruction methods.

1. Introduction

Phase sensitive optical coherence tomography (OCT) is able to measure small spatial fluctuations of an interface with sub-wavelength precision. As the reflected phase passes through a full 2π cycle for an effective axial displacement of half a wavelength, relative displacements can be measured at the level of tens of nanometers. However, when a low intensity reflector is in the vicinity of a high intensity reflector, the phase from the high intensity reflector can leak into the the signal of the other interface [1]. This hampers the ability to see relative motion between closely separated interfaces. This is especially significant when the axial distance between the reflectors is in the order of the axial resolution.

Spectral estimation OCT (SE-OCT) is able to improve the axial resolution over the bandwidth-induced limitation, creating super-resolution [2, 3]. In recent work, we presented SE-OCT based on the non-parametric iterative adaptive approach (IAA). Contrary to for example the auto-regressive method IAA is able to preserve phase information in the reconstruction. Using a weighted least square solution, with a weighting matrix based on the reconstruction, IAA suppresses the contribution of high intensity reflectors to other depths. This improves the axial resolution [3], but could also suppress spectral leakage to other depths.

In this abstract we explore the ability of IAA-based SE-OCT to suppress phase leakage and reconstruct relative motion of vibrating interfaces in the vicinity of a strong reflecting interface. Reducing phase leakage improves the axial sectioning ability of phase-sensitive OCT [4]. This could be useful in applications like vibrometry [5], especially when the axial resolution is sacrificed for extended imaging range.

2. Theory and methods

IAA uses a weighted least square method to obtain a high resolution estimate of the reflectivity $a(z_l)$ at depth z_l:

$$a(z_l) = \text{argmin}_{a(z_l)} |\mathbf{y} - a(z_l)\mathbf{f}_l|^2_{\mathbf{Q}_l^{-1}}, \quad l = 0, 1, \ldots, L-1, \tag{1}$$

where $\mathbf{y}$ is the uniformly reshaped interference spectrum, $\mathbf{f}_l = \left[\mathrm{e}^{-2\pi i z_l k_0} \ \ldots \ \mathrm{e}^{-2\pi i z_l k_N}\right]^T$ is the vector with corresponding Fourier components and $\mathbf{Q}_l$ is the covariance matrix of the data, excluding that for depth z_l. The inverse of the covariance matrix suppresses the contribution of high intensity reflectivity to other depths than the sought signal at z_l. This reduces the signal side-lobes, the main-lobe width, and also, for this contribution particularly important, phase leakage between signals at different depth. The solution for Eq. (1) is

$$a(z_l) = \frac{\mathbf{f}_l^H \mathbf{R}^{-1}\mathbf{y}}{\mathbf{f}_l^H \mathbf{R}^{-1}\mathbf{f}_l}, \quad l = 0, 1, \ldots, L-1, \tag{2}$$

where

$$\mathbf{R} = \sum_{l=0}^{L-1} |a(z_l)|^2 \mathbf{f}_l \mathbf{f}_l^H + \Sigma \tag{3}$$

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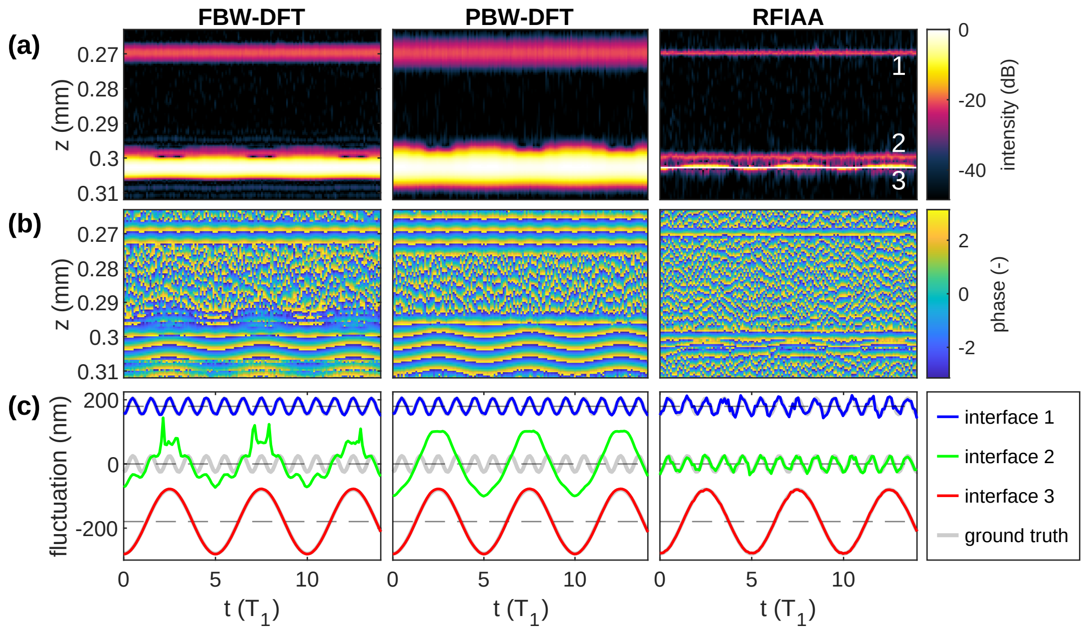

Fig. 1. Image and phase reconstruction based on simulated data. (a) The image intensity as function of depth and time. (b) The phase of the reconstruction in (a). (c) The reconstruction of the fluctuations of the interfaces based on the phase information, with an offset to separate the signals. The interface numbers are indicated in the right image in (a).

is the estimate of the data covariance matrix. Iterating 10 times between Eqs. (2) and (3) after initiating the optimization with $\mathbf{R} = \mathbf{I}$ (i.e. uniform weighting) refines the estimate of the reflectivity, giving a high resolution estimate.

While in previous work, $a(z_l)$ was transformed into intensity $|a(z_l)|^2$ and plotted on a log scale [3], as a complex quantity it also has a phase that can be used to sense sub-wavelength vibrations.

Simulation data from three vibrating interfaces was obtained using 1D OCT simulations [3]. The spectral shape, bandwidth of 160 nm, and center wavelength of 900 nm were used for the simulations (this corresponds to the parameters an existing spectral domain OCT setup [3]). The simulated spectral data has a length of 2048 pixels. Two interfaces with a low reflectance and a third interface with a 10 times higher reflectance (100 times higher intensity). One of the low reflectance interfaces was placed well separated from the other two, while the second interface was simulated only 3.0 μm above the high intensity interface, which is within the coherence length of the light source. The low reflectance interfaces vibrated with 1.2 kHz and an amplitude of 20 nm, while the high intensity surface vibrated with 0.25 kHz and an amplitude of 80 nm. The acquisition frequency is 36 kHz. Noise was added such that the low reflectance interfaces had an SNR of 36 dB and the high intensity surface had an SNR of 56 dB.

Three reconstruction methods were compared with each other. First, the conventional DFT reconstruction with an interference signal from the (Gaussian reshaped) full bandwidth (FBW-DFT) with a nominal resolution of 3.4 μm. Second, the DFT reconstruction with a partial bandwidth that has a Gaussian shape with 10% intensity at a width of 100 nm (1024 pixels) (PBW-DFT), having an axial resolution of 5.9 μm, and the recursive fast IAA (RFIAA) on a 100 nm (1024 pixel) length input spectrum. For RFIAA, the numbers of iterations were set to 10 for the first A-scan and 2 for the subsequent scans in the recursive scheme. The reconstruction grid was 4 times as dense as the nominal DFT reconstruction grid. The zero padding was applied with the DFT methods to obtain the same depth sampling density as RFIAA.

3. Results and discussion

Figure 1 shows the reconstruction results with the three methods. From the intensity images (a) it is clear that both DFT methods cannot well resolve the two bottom interfaces as their separation is sub-resolution. RFIAA can resolve these interfaces clearly, showing its ability to improve the resolution above the bandwidth-limited nominal resolution. All images shows some variations in the interfaces resulting from their vibration and the interference between the signals from these interfaces (DFT methods) or preference direction for small side-lobes (RFIAA). The phase image in (b) shows how the phase of the high intensity reflector influences the phase of a far region around the scatterer, including where interface 2 lies. RFIAA limits the region where the phase is determined by the interface to a narrow axial range.

When the phase is translated into depth fluctuation, as displayed in Fig. 1(c), we see clearly that for the DFT methods the second interface (green) is heavily influenced by the phase of interface 3. With the FBW-DFT method, the vibration of interface 2 is visible, but added to that of interface 3. With a smaller bandwidth (PBW-DFT), the high frequency vibration is not visible at all, and the phase is fully determined by the phase of interface 3. Using the same bandwidth as PBW-DFT, RFIAA clearly reconstructs the vibration frequency and amplitude of interface 2. This result shows the potential of RFIAA to reduce phase leakage.

However, we see that for interface 1, which is well resolved for all methods, the phase reconstruction is a bit more accurate with the DFT methods than with RFIAA. The difference in accuracy can be quantified using the root mean square (rms) difference between the reconstructed vibration and the ground truth. The obtained rms values are displayed in Table 1. Interface 1 indeed gives a larger error for RFIAA. A reason could be that the main lobe is only about a single pixel wide and if the peak is not located exactly at the pixel, the reconstruction is more influenced by the noise. Increasing the upsampling ratio indeed improves the accuracy a little bit. Still, the error is larger for this interface. However, for interfaces 2 and 3, RFIAA outperforms both DFT methods as it reduces the influence of the other peaks.

Table 1. Root mean square (rms) of the difference between ground truth and the reconstruction in Figure 1(c) for the fluctuations for each interface for the different methods.

Interface	FBW-DFT	PBW-DFT	RFIAA
1	1.3 nm	1.5 nm	3.9 nm
2	28 nm	52 nm	4.3 nm
3	0.8 nm	1.0 nm	0.7 nm

The simulation results in this abstract clearly show that RFIAA gives an accurate phase reconstruction and limits phase leakage between interfaces. Besides vibrometry, RFIAA may also improve the accuracy of other phase-based OCT imaging, such as Doppler OCT.

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