Optical Coherence Tomography and Profilometry based on Optical Sampling by Cavity Tuning

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Abstract: We report the demonstration of an optical coherence tomography and surface profilometry system based on optical sampling by cavity tuning. Our scheme provides a simple, cost-effective solution for rapid, large-depth noninvasive imaging.
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1. Introduction

High-speed tunable optical delays (TOD) with large tuning depths are universally needed in such important areas as optical interferometry, optical coherence tomography (OCT), pump-probe spectroscopy and Fourier-domain spectroscopy. In recent years, novel TOD approaches based on ultrafast lasers and optical frequency combs have made considerable progress in terms of both scan rate and scan depth [1-5]. For example, asynchronous optical sampling (ASOPS), which employs two femtosecond lasers with slightly detuned repetition rates, has demonstrated scan of optical delay as fast as 100 kHz with total scan ranges up to 30 cm at 10-kHz [1]. ASOPS-based OCT has achieved an imaging depth of 150 mm at an acquisition rate of several kilohertz [2]. Despite these improvements, ASOPS suffers a major drawback as it requires two femtosecond lasers and a complex phase-lock system, which adds significant cost and complexity to the scheme. To address this problem, an alternative scheme called optical sampling by cavity tuning (OSCAT) has recently been developed [3-6]. OSCAT aims to use one single femtosecond laser to attain similar tunable pulse relative delays as in ASOPS. The method is to add an intra-cavity modulation to tune the pulse repetition rate and let the produced pulse train go through an interferometer with highly mismatched arm lengths. The combination of the repetition-rate modulation and the path-length mismatch, as has been shown previously [4,5], creates a scan of the relative pulse delay at the rate of the modulation. Since intra-cavity piezo-electric (PZT) actuators can reach a tuning rate as fast as 180 kHz [7], OSCAT can potentially achieve centimeter-scale TOD at a rate greater than 100 kHz [5].

In this report, we experimentally demonstrate OCT and three-dimensional (3D) surface priofilometry based on OSCAT. The motivation is to take advantage of the potentially very large (cm scale) scan depth of OSCAT for novel applications such as industrial process control and remote target identification.

2. Experimental Setup and Result

Our experimental setup is shown in Fig. 1(a). Detailed specifications about this setup can be found elsewhere [5]. To operate our OSCAT imager, we first find the cross-correlation signal from a reference surface, which is typically a known flat surface such as the substrate of the sample. This is done by sweeping the intra-cavity stage and hence scanning the repetition rate across a relatively large range. Once this reference point is found, we fix the stage and modulate the intra-cavity PZT actuator to perform the axial scan, or A-scan. The maximum relative pulse delay is related to the repetition rate modulation by $\Delta l_d = (\Delta f_R / f_{R0})\Delta l_i$, where Δl_d is the pulse delay in terms of free-space length, Δf_R is the peak-to-peak variation of the repetition-rate, f_{R0} is the nominal repetition rate, and Δl_i is the arm-length mismatch of the interferometer. In our case, $\Delta f_R = 3.55$ kHz, $f_{R0} = 250$ MHz, and $\Delta l_i = 1.39$ km, which yields $\Delta l_d = 1.97$ cm. In other words, our OSCAT system is able to map structures about 1 cm deep in free space (considering round trips), which has been demonstrated in an earlier experiment [5]. This depth can be further extended by either increasing the arm-length difference Δl_i or increasing the ratio $\Delta f_R / f_{R0}$.

Various kinds of samples have been tested in order to explore the versatility of the scheme. Fig. 1(b) shows the cross-sectional image obtained from a sample of two plastic foam bubbles set above a glass substrate. The white lines in the images indicate the reflection surfaces in the sample. The upper lines indicate the top surfaces of the two bubbles while the lines in the middle indicate the bottom layer of the foam. All the A-scan measurements are aligned by the bottom line which indicates the surface of the glass substrate. The shape of the bubble foam is clearly sketched out by the yellow fitted line in Fig.1 (b). Fig. 1(c) is an OCT image of a multi-phase sample in a plastic container, consisting of washing liquid and air bubbles. The interfaces between the different phases of the sample, such as air and liquid (top), liquid and plastic (middle), plastic and air (bottom) are revealed by the imager. Again, all the A-scan measurements are aligned by the bottom line which indicates the bottom surface of the plastic container. The white dots between top and middle lines indicate the locations of reflections on the interfaces between the liquid and air bubbles. The dots are artificially enlarged for clearer view. Combining the A-scan and a two-axis transverse scan, a 3D image of the reflection points in a volume of the multi-phase sample is also obtained as shown in Fig. 1(d). The scan area of the sample is 3×5 mm, producing 1500 A-scans with an increment of 100 μm. The gray dots indicate the single reflections while the colorful dots indicate different clusters of reflections. The bubbles have different sizes and these clusters could be reflections from surfaces of big air bubbles.

Another important application of DROI is remote 3D surface profilometry. Combining the A-scan and a two-axis transverse scan, we have mapped the letter "H" on a UAH key chain into a 3D profile, as shown in Fig. 1(e). The key chain, which is pictured in Fig. 1(e), is mounted flat on the two-axis translation stage, and is about 5 cm away from the beam-focusing lens. The transverse scans produces an 80×72 mesh with an increment of 250 μm, and an A-scan is performed at each point on the mesh. For simple surface profiling, only the depth information is extracted from each A-scan and that leads to a 2×2 matrix of surface height and the 3D graph shown in Fig. 1(e). The sub-100-μm indent of the letter is clearly mapped out by the imager.

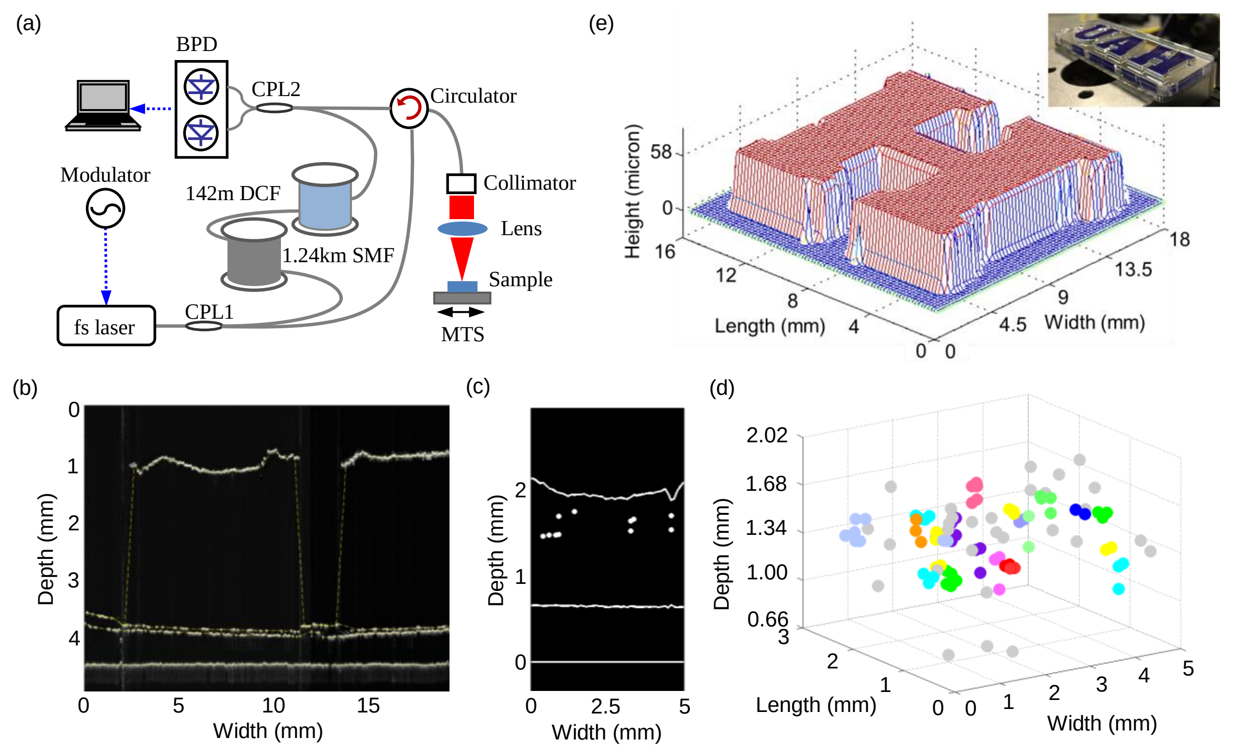

Fig. 1. (a) Schematic of the OSCAT OCT system. CPL, optical coupler; DCF, dispersion compensating fiber; SMF, single-mode fiber; and BPD, balance detector; (b) image of a bubble foam on a glass substrate; (c) A 3D surface profile of the letter "H" on a UAH key chain obtained by the OSCAT imaging system and an actual picture of the key chain; (d) An OCT image shows the cross-sectional structure of a multi-phase sample consisting of washing liquid and air bubbles, the interfaces between air and liquid (top), liquid and plastic (middle), plastic and air (bottom) are revealed by the imager. The white dots between top and middle layer indicate reflections on the interface between liquid and air bubbles. The dots are enlarged for clearer view. (e) A 3D image shows the locations of reflections on the bubbles in a volume of the multi-phase sample.

3. Reference

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