

Phase-sensitive OCT on a silicon photonic chip: characterization and functional ear imaging

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Abstract: We demonstrate the phase stability of a fully integrated chip-scale OCT interferometer for clinical otology applications, capable of imaging sub-nanometer vibrations in the middle ear and mapping the tympanic membrane vibrational modes. © 2022 The Author(s)

1. Introduction

Optical coherence tomography (OCT) is a non-invasive 3D imaging technique widely used for imaging the eye [1], with growing interest for imaging other clinically relevant organ systems such as the ear [2]. Nevertheless, OCT remains a bulky and expensive tool which has significantly limited its widescale adoption. Recently developed handheld extensions of OCT subassemblies for in-ear imaging have shown 3D subsurface details like layers and thickness of the tympanic membrane and position and dimensions of the ossicles, as well as functional vibrometry of the tympanic membrane and other structures within the middle ear [3]. Functional vibrometry using an OCT device leverages the time-varying interferometric phase from a fast-moving sample and is extremely vulnerable to sources of phase noise in the optical path. Recently, Eggleston et al. demonstrated the first ever fully integrated chip-scale OCT engine comprising an ultra-low loss planar lightwave circuit (PLC) interferometer, integrated balanced photodiode pairs, a collimating ball lens, and a co-packaged thermally actuated MEMS mirror for scanning [4]. The chip-scale OCT can be integrated into low-cost portable devices for diagnosis and surgical guidance. Its ability to perform measurements with low phase-noise furthers its capacity for applications built on phase-sensitive OCT, e.g. Doppler OCT [5], OCT elastography [6] and OCT vibrometry [3]. Here we show that this PLC-based OCT system can achieve a phase sensitivity of ~ 0.1 nm in a scattering sample. Furthermore, we demonstrate it for *in vivo* imaging of the mouse middle and inner ear.

2. Experimental Details

In this work we use a swept-source OCT (SS-OCT) configuration as depicted schematically in Fig. 1a. The system is comprised of four main components: 1) a portable scanner with integrated optics engine (PLC; balanced diodes; ball lens), beam scan control (biaxially scanning MEMS mirror), a transimpedance amplifier (TIA), 2) an off-board commercial swept-source laser (Insight, 1310 nm center wavelength, 40 nm sweep bandwidth, 90 kHz sweep rate), 3) an audio stimuli setup (Fostex), and 4) the DAQ and data processing assembly on an off-board PC comprising a digitizer (ATS9371, 12 bit, 1GSa/s, AlazarTech Inc.) and customized GUI (Python, C++, and CUDA). The on-board electronics are powered using a 12V DC power supply, the off-board laser is coupled to the scanner using a single mode fiber, and the drive electronics and DAQ communicate with the scanner using coaxial cables.

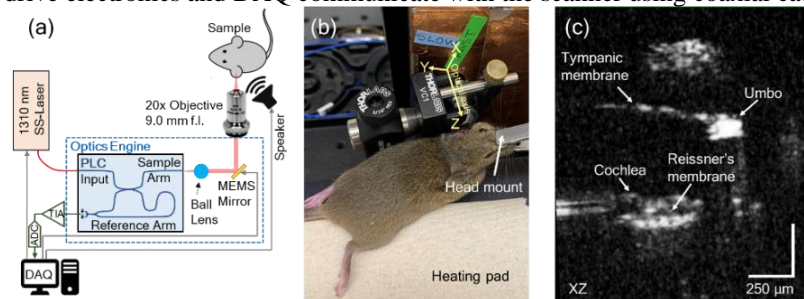


Fig. 1. (a) Schematic diagram of the compact OCT system, (b) *in vivo* imaging setup with live mouse, (c) OCT cross-sectional of mouse middle ear region.

The OCT signal processing for vibrometry has been detailed previously [2] and is only briefly described here. Based on the cross-sectional B-scan images (1.8 mm wide, 180 pixels, 10 μ m resolution) generated by linearly raster

scanning the MEMS at ~ 220 Hz [7], a region/point of interest is selected for vibrometry. The MEMS mirror waveforms are designed to enable 50 ms residence time over each pixel in the presence of vibrations. During this period, the interferometric signal is consecutively recorded and processed to generate a complex OCT signal. The time-varying interferometric phase along each 50 ms segment is then extracted and unwrapped, followed by low frequency drift removal by subtracting a 3rd order polynomial fit to the entire phase. A second fast Fourier transform along the time-domain phase signal results in a frequency domain plot of the magnitude of phase change, scaled to displacement with a $\lambda/(4\pi n)$ multiplication factor, where $\lambda = 1310$ nm, n is the sample refractive index.

3. Results and Discussion

We characterize the system using several metrics. First, using a perfect reflector (Ag mirror) and 2.3 mW sample arm power, the system SNR was measured to be 101.71 dB (theoretical 107.27 dB). Second, for vibrometry, a piezo with multilayer 3M scotch tape was driven by 4 kHz sinusoidal signal during a 50 ms acquisition time, resulting in a mean and standard deviation phase noise values of 0.162 and 0.0380 nm, respectively (theoretical 0.072 and 0.037 nm [8], respectively). The frequency response of the top surface of the multi-layered scotch tape, used for the vibrometry evaluation above, is plotted between 0 to 25 kHz (see Fig. 2b)

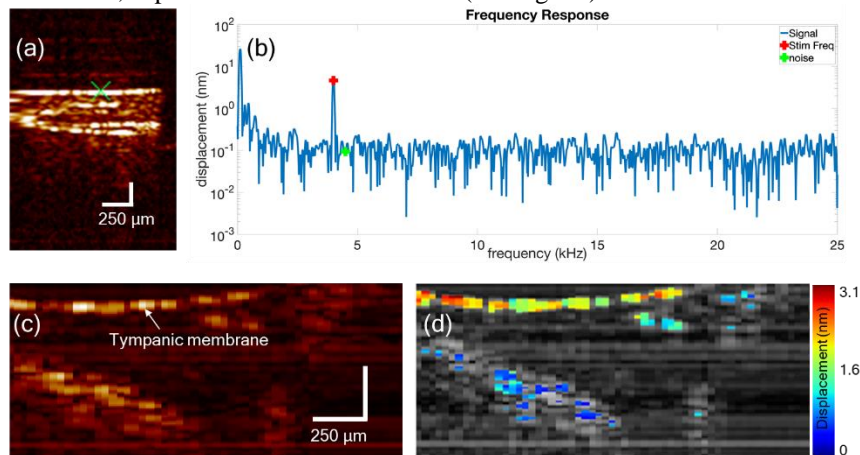


Fig. 2. (a) OCT image of piezo with scotch tape and (b) its frequency response. (c) Cross-section OCT image of mouse tympanic membrane and (d) its vibrational displacement when excited with 4 kHz audio stimuli.

We then tested the device for in-vivo imaging of live mouse as shown in Fig. 1b. The animal tests were performed under the protocols approved by the Institutional Animal Care and Use Committee at the University of Southern California. The pinna and adjacent skin were removed for easy access to the middle ear, and the mouse ear canal was positioned along the imaging axis using a custom head mount. The grayscale cross-sectional OCT image of the mouse middle ear is shown in Fig. 1c, and the zoomed-in tympanic membrane region without audio stimulus is highlighted in Fig. 2c. Upon stimulation with 4 kHz pure tone, the tympanic membrane was displaced up to 3.1 nm, as represented by the overlaid color image in Fig. 2d.

In conclusion, we have characterized the sensitivity of a chip-scale OCT system for functional and morphological imaging. Such a high-sensitivity chip-scale system is a key component for future fully integrated OCT systems for low-cost and portable 3D imaging devices for clinical diagnostics.

4. References

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