# 90dB Sensitivity in a Chip-Scale Swept-Source Optical Coherence Tomography System

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**Abstract:** Record high sensitivity of 90dB is achieved in a chip-scale SS-OCT system. A PLC interferometer, on-chip balanced diode pair, and ball lens coupled MEMS mirror form an ultra-compact optical engine for 3D imaging.

**OCIS codes:** (110.4500) Optical coherence tomography; (230.3120) Integrated optics devices.

## 1. Introduction

Optical coherence tomography (OCT) is a high-speed 3D imaging technique that has shown rapid development recently and increased use in clinical applications such as retinal imaging, optical biopsies of the skin, and cardiovascular imaging. It offers penetration depth into tissue up to several millimeters and can achieve lateral and depth resolution below 10um.

OCT remains an expensive tool (~$100k) with limited portability which has significantly limited its widescale availability and use. Recent work to miniaturize OCT to the chip-scale using integrated optics has mainly relied on bulky external beam-steering optics and an external interferometer [1], [2] with integrated photonics only providing the optical detection portion. Previous attempts to use an on-chip interferometer were limited in sensitivity to -53dB due to high losses on and off-chip and large backscatter noise in silicon waveguides [2]. To enable a truly chip-scale integrated OCT system for ultimate portability and low cost, the beam-steering optics, interferometer, and optical detection all need to be cointegrated on a chip.

In this work we demonstrate for the first time ever a fully integrated chip-scale OCT optical engine comprised of a Planar Lightwave Circuit (PLC) interferometer, integrated balanced photo-diodes, and a co-packaged thermally actuated MEMS mirror. We achieve a sensitivity of -90dB with an optical power of 550uW on the sample, enabled by the ultra-low loss of the PLC platform. Such a platform is an important step towards fully-integrated OCT systems that could be incorporated into portable electronics such as wearables and mobile phones for low-cost ubiquitous 3D imaging.

## 2. Integrated OCT System

In this work we use a swept-source OCT (SS-OCT) configuration as depicted schematically in Fig.1(a). The system is comprised of three main components: 1) a portable scanner "puck" with integrated optics engine, beam scan control, and a transimpedance amplifier (TIA), 2) an off-board commercial swept-source OCT laser (Axsun, 1310nm center wavelength, 140nm sweep bandwidth, 100kHz repetition rate), and 3) a mini-computer with a two channel, 16bit, 1 GSample/sec analog-to-digital (ADC) converter card. The off-board laser and electronics are coupled to the scanner with a single mode fiber, coaxial cable, and USB cable which provides power and communication with the beam sweep controller.

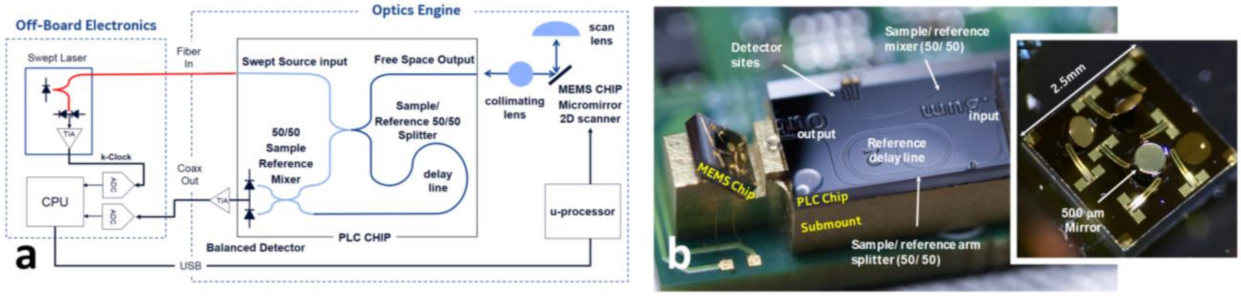

*Figure 1. (a) Schematic diagram of the compact OCT system, showing the main components of the Optics Engine and off-board electronics. (b) Partial view of the actual OCT Optical Engine. (inset) Detail of the MEMS mirror and 4 thermal actuators.*

Fig.1(b) shows the physical realization of the Optical Engine shown schematically in Fig.1(a). It consists of a PLC interferometer with integrated photodetectors (PD), coupled to a MEMS 2D scanning mirror by a ball lens, all mounted on a 20mm x 6mm CNC-machined metal submount, which is glued to a rounded 3.5cm x 3.5cm PCB with active components wire-bonded to the detection and driving electronics. The entire PCB is mounted in a 3D printed plastic puck measuring 5cm in diameter and 2cm thick. The top of the puck is closed with a 3D printed lid containing a 4mm focal length scan lens that is aligned directly over the MEMS mirror.

The scanning micromirror was fabricated in the PolyMUMPS process by MEMSCAP [3], and is similar to the one described in Reference [4]. A Poly1/Poly2 500 μm diameter mirror with a radius of curvature of 100 mm is driven by 4 thermal actuators. A soft Poly2 serpentine spring connects the mirror with each of the actuators. Each actuator is made of a Poly2/Metal stack with a stress gradient across its thickness, bending upwards upon release. Joule heating combined with the differential thermal expansion coefficients between the two materials in the stack flatten each actuator towards the substrate at about 40mW. By suitable combination of the electrical power dissipated in each actuator, piston (~200μm displacement) and tip tilt motion (+/-13° mechanical) can be obtained in our driving system. The thermal time constant for these actuators is ~3ms, with overdamped characteristics, with a higher frequency mechanical resonance at ~1kHz (Q of ~10) for the mirror-supporting springs system. A two-step driving scheme [5] was easily implemented in the microprocessor to suppress this potentially long settling time of more than 10ms.

The CNC-machined metal submount provides a rough mechanical XYZ and angular positioning (not better than 50 μm) for the PLC and MEMS chips, such as the core of the waveguide is aligned to the center of the MEMS mirror at 45°. Next, a laser source is connected to the PLC and a 500μm glass ball lens, AR-coated for the O-band, is placed between the two and moved until a narrow, collimated beam is obtained at the imaging plane. A drop of UV-curable cement at the machined pedestal right below the lens location fixes it in place. Although done manually in this work, the entire assembly process, including lens pick-up, active optical alignment, epoxy dispense and curing, can be automated using a programmed stage system [6]

## 3. Optical Measurement Results

The analog OCT signal from the TIA is fed through a coaxial cable to an external computer, digitized and then processed with an Intel i7 CPU. The signal is resampled using the swept-laser's k-clock and converted to distance using an FFT. Two A-scans (axial scans) are averaged to create a single depth scan and the laser spot is scanned over an area of 1.3mm x 1.3mm. Resultant 3D images of a fingertip are shown in Fig.2(b). A neutral density filter and silver mirror was used to measure a system sensitivity of -90dB.

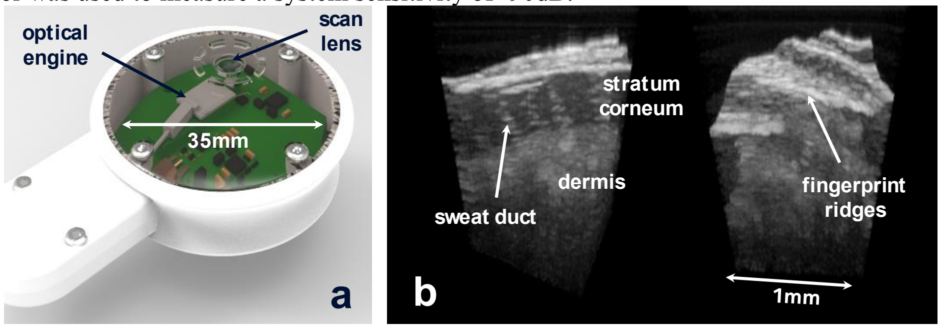

*Figure 2. (a) OCT head. PCB board with mounted optical engine. (b) Two views of the in-vivo 3D rendered OCT data of approximately 1.3x1.3x1.5mm$^3$ region of a fingertip.*

## 4. Conclusions

We have demonstrated the first chip-scale SS-OCT optical engine with integrated interferometer, detectors, and micro scanning mirror. The ultra-low loss PLC platform enables a sensitivity of -90dB and the integrated thermally actuated MEMS provide a scanning area of 1.3mm x 1.3mm. Such a high-sensitivity chip-scale system is a key component of future fully integrated OCT systems for low-cost and ubiquitous 3D imaging.

*C. Pollock and D.J Bishop work was supported in part by the Engineering Research Centers Program of the National Science Foundation under NSF Cooperative Agreement No. EEC-0812056. Authors would like to acknowledge Edward Sutter for assistance in the lab.*

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