# Chip-Based Frequency Combs for High-Resolution OCT

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## Abstract:

**We demonstrate chip-based frequency combs as a novel source for optical coherence tomography (OCT). For the first time an OCT image of human tissue is acquired using a silicon nitride microresonator. The potential for ultrahigh-resolution optical coherence tomography (UHR-OCT) is shown.**

## Summary of Research:

Optical coherence tomography (OCT) is a well-established medical imaging modality that has been used in fields such as ophthalmology, cardiology and dermatology [1-3]. Near infrared light sources with a full width half maximum (FWHM) bandwidth over 150 nm may allow for an axial resolution down to one micrometer in tissue [4]. An OCT broadband light source that can simultaneously achieve both, large bandwidth and deep signal penetration, remains out of reach.

Superluminescent diodes (SLDs), widely used in commercial OCT systems, have typical spectral bandwidths of up to 100 nm. Multiplexing of SLDs represents a viable approach to increase the bandwidth, but the overall achievable bandwidth is still limited by the gain medium. On the other hand, supercontinuum (SC) sources could in principle be used to achieve high resolution OCT. However, SC generation relies on pulsed lasers with kW-range peak power [5] and it suffers from instabilities in the output intensity and irregularities in the spectral shape, as a result of the complex interplay of linear and highly nonlinear effects during its generation [6].

Here we present a novel source for OCT based on chip-scale lithographically-defined microresonators with potential for sub-micrometer axial resolution and deep penetration. When optically pumped with a low-power continuous-wave laser source, they can generate broadband frequency combs. Such frequency combs have been demonstrated in numerous chip-scale platforms in the past decade [7-13]. The parametric gain in these photonic structures enables ultra-broad optical bandwidths which can exceed an octave [11-13] in contrast to traditional gain materials and is not limited by the gain bandwidth tradeoff.

We use an ultra-low loss silicon nitride resonator with a large cavity length of 1.9 mm in order to ensure that the generated frequency

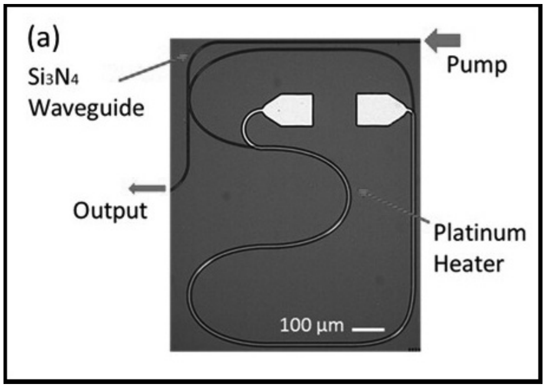


*Figure 1: Microscopy image of the silicon nitride on-chip microresonator.*

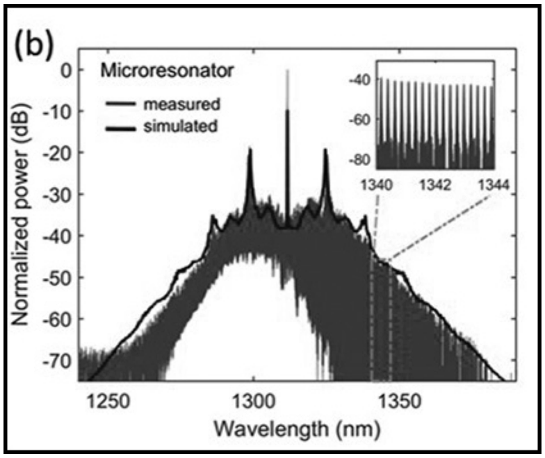
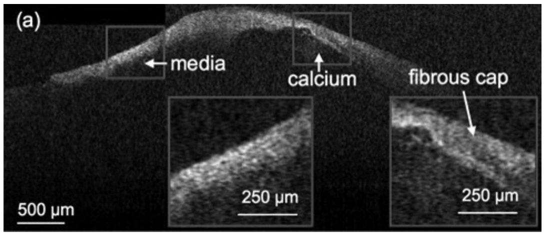


*Figure 2: Purple: Measured frequency comb spectrum generated using the silicon nitride microresonators. Black: Simulated frequency comb. See full color version on pages xxviii-xxix*



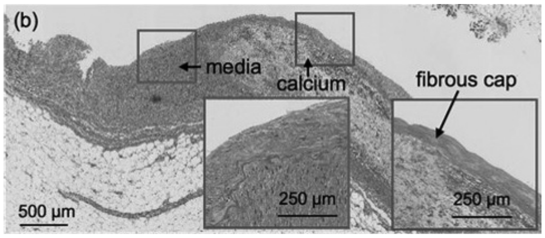


***Figure 3, left:*** *A stitched frequency-comb-based OCT B-scan of human coronary artery with a fibrocalcific plaque. Critical features are observed, including fibrous cap thickness, calcium, and media are depicted in OCT images, indicating a great potential for clinic applications.* ***Figure 4, right:*** *H&E histology.*

comb has small line spacing critical for large imaging range. Our resonator design leads to a line spacing (38 GHz), which makes it compatible with current OCT spectrometers. Figure 1 shows the fabricated resonator. Using optical pump power as low as 117 mW, we generated frequency combs with a 38-GHz frequency spacing (shown in Figure 2).

The generated frequency comb spectrum has a FWHM of 47 nm corresponding to a theoretical axial resolution of 16.3 $\mu$m in good agreement with our measured FWHM of the axial point spread function of 18 $\mu$m. In order to perform OCT imaging a comb with low temporal coherence is required. We ensure that the comb lines are not locked in phase by tuning of the cavity resonance relative to the pump frequency using a mircoheater that is integrated on the chip. In order to generate these frequency combs, we use pump source of a low-cost distributed feedback (DFB) laser. The microresonator platform could enable inexpensive sources for OCT since it leverages mass fabrication on wafer-scale and allows miniaturization of OCT systems. Also, this platform has the potential to generate combs an octave span to enable UHR-OCT.

We acquire OCT images of human tissue with a standard commercial spectral domain (SD)-OCT system using the microresonator platform. Figures 3 shows *ex vivo* OCT of human coronary samples imaged with our microresonator frequency comb source using a commercial SD-OCT system. Sections of tissue were stained with hematoxylin and eosin (H&E). A pathologist who specializes in cardiovascular pathology annotated coronary tissue structure in histology image. Figure 3 shows a stitched frequency-comb-based OCT image of a human left anterior descending artery in comparison with the H&E histology in Figure 4. OCT B-scans were stitched using the method previously used in cervical image processing [14]. In the red inset, a gradually decreasing trend of backscattering can be visualized within the transition region from a fibrous region to the media. The right inset in Figure 3 reveals a typical pattern of a fibrocalcific plaque [15], where a layer of signal-rich fibrous cap is on the top of calcium, a signal-poor region with a sharply delineated border. Importantly, overlying the fibrocalcific plaque region, we observe a thickness change from dense fibrous cap for stable plaque structure to thinner fibrous cap for unstable plaque structure, the latter of which has been found in great frequency in patients with acute coronary syndrome and acute myocardial infarction.

In summary, we have demonstrated the first OCT imaging based on a chip-scale source. We expect that miroresonator frequency combs have great potential for UHR-OCT.

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