

Optoacoustic Mesoscopy based on Laser Diodes

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Abstract: Herein, we report a new method for high-resolution optoacoustic mesoscopy based on laser diodes. We demonstrate that our method can achieve depth resolutions comparable to traditional laser sources, offering significant size and cost advantages.

1. Introduction

Raster scanning optoacoustic mesoscopy (RSOM) has reshaped the medical imaging domain by combining the unique advantages of optical microscopy and ultrasound imaging. Optoacoustic (OA) mesoscopy provides optical-level image contrast and structural resolution while maintaining acoustic-level depth resolution, enabling a wide range of new non-invasive imaging applications. However, commercial RSOM systems have suffered from their large size, high cost, and high complexity, which has hindered their translation into the clinic. Illumination sources in particular have been identified as one of the major contributors to this problem. Traditional laser sources such as diode-pumped solid-state (DPSS) lasers have been shown to be slow, complex, costly, and bulky [1]. Low-cost illumination sources, such as laser diodes, are a promising alternative but have thus far not been able to achieve the same spatial and depth resolving capabilities as DPSS lasers. However, by leveraging advances made in overdriven laser diode optoacoustic microscopy and OA signal processing [1], this work demonstrates high-resolution OA mesoscopy based on laser diodes for the first time, offering a new path to miniaturized, low-cost RSOM systems.

2. Methods

2.1. Hardware Design

A custom-built laser diode (LD) driver board and triggering module were developed and integrated into a custom-built RSOM system, comprised of analogous components to the commercial RSOM Explorer C50 research system. The illumination module consisted of a 450 nm laser diode wired in parallel with a 532 nm commercial DPSS laser, enabling on-demand switching between the two light sources. The acquisition module consisted of a 50 MHz transducer and a data acquisition unit. Raster scanning was done using a compact linear XY stage.

2.2. Digital Signal Processing and Image Reconstruction

The following methodology was used for signal processing and image reconstruction: Firstly, all signals acquired under both light sources underwent motion correction to correct for motion artifacts [2]. Then, OA signals acquired from laser diode scans underwent pre-processing to clean and filter the raw data before reconstruction. The pre-processing steps included signal averaging to boost the signal-to-noise ratio (SNR) of the data, and digital signal deconvolution to remove the characteristic noise from the signals. OA signals from both light sources were then individually reconstructed [3]. Lastly, reconstructed images were visualized using the maximum intensity projection.

2.3. Animal and Clinical Study

An animal study was performed to get a preliminary assessment of data quality between LD acquisitions and DPSS acquisitions. Raster scan measurements were taken dorsally on the right and left lower back regions of high-fed diet albino BL6 mice. Additionally, clinical scans of the forearm were acquired on two different participants. The study protocol was approved by the ethics committee of the Technical University of Munich; all participants gave their written consent. The resultant scans were reconstructed and visualized according to the aforementioned protocol.

3. Results

To assess our method, reconstructed images from the 450 nm laser diode were compared to the 532 nm DPSS laser for both animal and clinical measurements. Furthermore, the laser diode images were reconstructed with and without raw signal processing to assess the impact of our digital signal processing techniques on the image quality. The resulting images were analyzed qualitatively by performing feature matching, using the 532 nm scans as a baseline.

Reconstructed images from the clinical pilot study (see Fig. 1 & Fig. 2) show that the raw OA signals from the laser diodes present a baseline noise level (represented by the green background noise in Fig. 1 (A)) that blurs the raw data and makes select individual features difficult to distinguish. This is particularly visible when comparing Fig. 1 (A) and Fig. 2 (B), where there are relatively few comparable features between the two images. However, as can be seen in Fig. 1 (B), when our raw signal processing technique is applied to the laser diode data, there is marked improvement in image quality. Not only are significantly more features discernible in Fig. 1 (B) compared to Fig. 1 (A), but imaging contrast, spatial resolution, and depth resolution are all visibly higher. Features that were hidden by noise in Fig. 1 (A), particularly in the upper epidermis and the subcutaneous vasculature, are clearly visible in Fig. 1 (B). Furthermore, the additional features in Fig. 1 (B) directly correspond to the remaining visible features in Fig. 2 (B). Lastly, as can be seen in Fig. 2, the restoration of anatomical features shown in Fig. 1 results in depth resolving capabilities that are on par with DPSS lasers, showing that a significant technical gap is closed by our method. Collectively, these results demonstrate that our raw signal pre-processing method is effective at boosting the LD image quality to a level that is directly comparable with DPSS lasers, making LD optoacoustic mesoscopy possible.

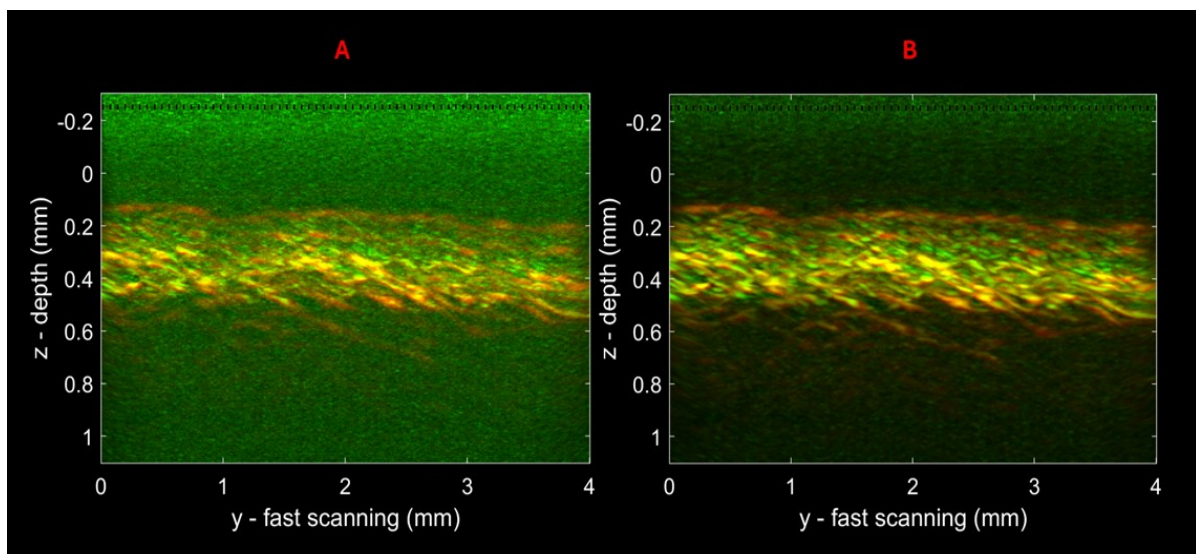


Fig. 1. Reconstructed RSOM images from the clinical pilot study showing image quality improvements through digital signal processing. A) 450 nm laser diode (without raw signal processing), B) 450 nm laser diode (with raw signal processing)

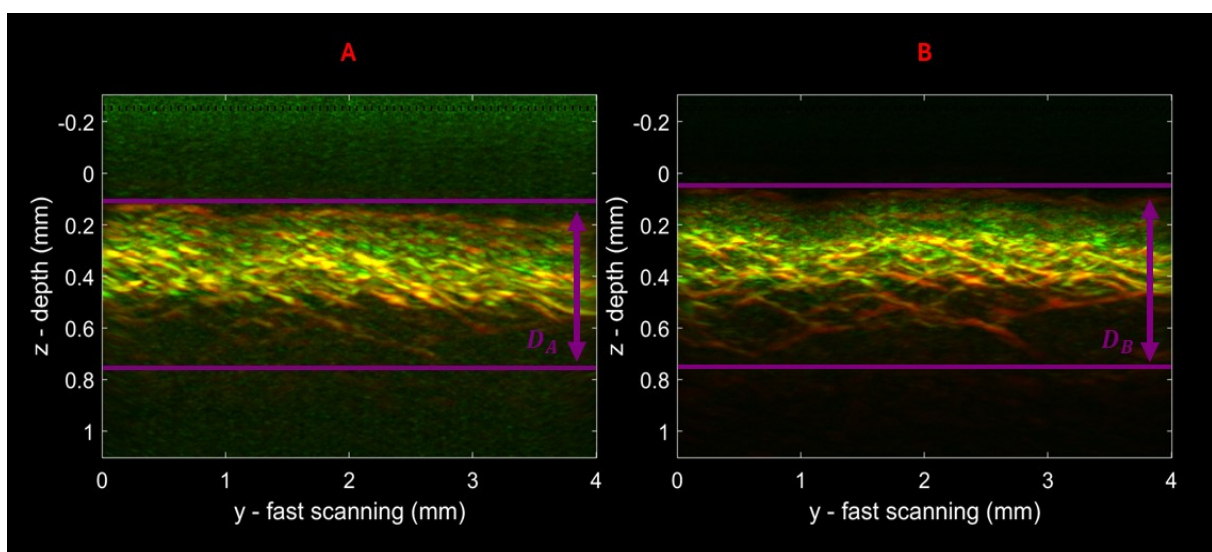


Fig. 2. Reconstructed RSOM images from the clinical pilot study showing a depth resolution comparison between LD- and DPSS-driven optoacoustic mesoscopy. A) 450 nm laser diode (with raw signal processing), B) 532 nm DPSS laser.

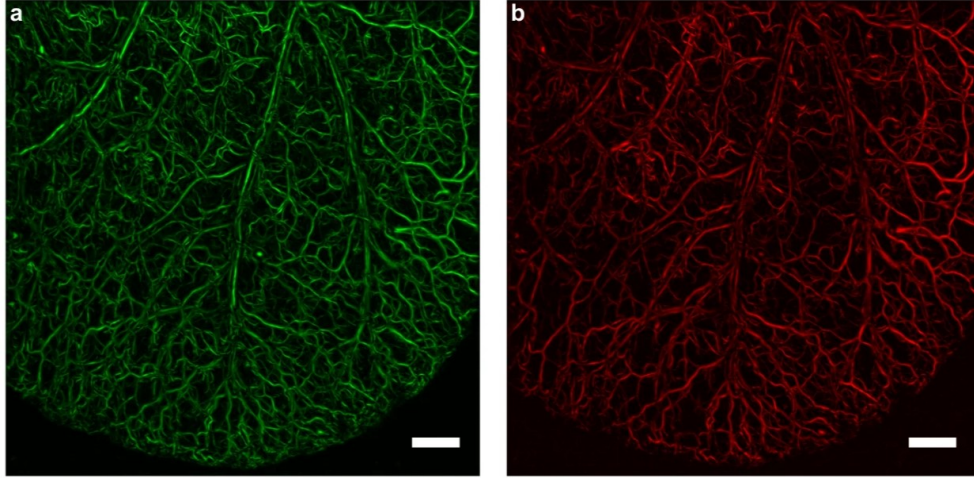


Fig. 3. A high-resolution overdriven laser diode optoacoustic microscopy image of a mouse ear at (A) 445 nm and (B) 465 nm, adapted from Stylogiannis et al. (2022) under a CC-BY 4.0 license [4].

4. Discussion

In this work, we present a novel technique for high-resolution optoacoustic mesoscopy using laser diodes. This approach leverages hardware advances made in overdriven laser diode optoacoustic microscopy, as well as handcrafted pre-processing algorithms to boost SNR and remove the characteristic noise of the data. The results show that our technique results in significant image quality improvements, including imaging contrast and spatial resolution. Most notably, we demonstrate that our method successfully closes the gap in depth resolution between LDs and DPSS lasers, which is a significant barrier to LD-driven optoacoustic mesoscopy. Previous studies have demonstrated high-resolution optoacoustic microscopy using overdriven laser diodes, as can be seen in Fig. 3 [4]. However, unlike microscopy, mesoscopy requires significantly more depth penetration to get any meaningful data. Traditionally, laser diodes have struggled to attain significant depth penetration due to their lower average pulse energy compared to DPSS lasers. This study shows that digital signal processing techniques can help overcome that barrier by recovering deeper information from LD-based RSOM scans, paving the way for practical LD-driven OA mesoscopy. Although a true 1:1 correspondence between laser diodes and DPSS lasers is not yet achieved in terms of spatial resolution, this work shows that significant gains are possible using digital signal processing. We speculate that the remaining image discrepancies are largely due to laser pulse energy and wavelength differences. Nevertheless, we assert that the marginal drops in signal quality and resolution are acceptable given the order-of-magnitude reduction in cost, size, and complexity from DPSS lasers, particularly in low-cost, miniaturized systems.

5. Acknowledgements

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6. References

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