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# Continuous wave laser diodes enable fast optoacoustic imaging

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ABSTRACT

Pulsed laser diodes may offer a smaller, less expensive alternative to conventional optoacoustic laser sources; however they do not provide pulse rates faster than a few tens of kHz and emit at wavelengths only within the near-infrared region. We investigated whether continuous wave (CW) laser diodes, which are available in visible and near-infrared regions, can be good optoacoustic light sources when overdriven with a peak current >40-fold higher than the CW absolute maximum. We found that overdriven CW diodes provided ~10 ns pulses of ~200 nJ/pulse and repetition rates higher than 600 kHz without being damaged, outperforming many pulsed laser diodes. Using this system, we obtained images of phantoms and mouse ear and human arm *in vivo*, confirming their use in optoacoustic imaging and sensing.

## 1. Introduction

Optoacoustic measurements are typically performed by employing light pulses in the nanosecond pulse-width range. Ultra-short pulses are important for satisfying stress and thermal confinement requirements and for maximizing the signal-to-noise ratio (SNR) and the imaging resolution achieved [1–6]. Fast pulsing rates are also important as they can accelerate raster-scan times in imaging applications and possibly further improve the SNR through signal averaging. An additional critical parameter of optoacoustic illumination is the energy per pulse delivered to tissue. Clinical and small animal optoacoustic systems considered for macroscopic imaging at depths of several millimeters to centimeters require nanosecond pulses of 10–100 mJ/pulse [7]. Such energies are typically delivered by expensive, slow and technologically complex lasers, such as Q-switched Nd:YAG or dye lasers, which attain large form factors and can require forced cooling and frequent realignment. Optical parametric oscillators (OPOs) or different dyes impart the ability to generate different wavelengths, but this further increases cost and complexity of the illumination source.

Compared to macroscopic imaging, optoacoustic microscopy and mesoscopy typically operate at depths in the micrometer and millimeter range [8], respectively. Several microscopy or mesoscopy implementations have been based on pulsed-OPO or dye laser technology [9], typically using more cost-effective laser versions compared to macroscopy, due to the lower energy-per-pulse requirements. Nevertheless, pulsed OPO and dye laser technologies are not appropriate for miniaturization or drastic cost reduction.

Alternatively, light-emitting diodes (LED's) and laser diodes can be considered for optoacoustic signal generation due to their small size, low cost, commercial availability, high repetition rate tolerance, stability and ability to operate without an external active cooling system [10–14]. LED's feature emitting areas of approximately 1 × 1 $mm^2$ and no output facet reflectivity. LED's are available in a wide range of wavelengths including the visible and the near-infrared (NIR) region. Moreover, they generally provide energies on the order of a few $\mu$J up to a few hundred of $\mu$J/pulse, although with a relatively long pulse width on the order of 100–500 ns. Commercially they are also available in stacks of multiple LED's in order to increase the output power. Due to their large emitting region, long pulse width and higher energy output, they are suitable only for broad-field illumination and have been used only in tomography systems such as in [12], achieving penetration depths of 15 mm and lateral resolution of ~500 $\mu$m.

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*Abbreviations:* CNR, contrast to background ration; COD, catastrophic optical damage; CW, continuous wave; DAQ, data acquisition card; FWHM, full width at half maximum; MIP, maximum intensity projection; NIR, near-infrared; OPO, optical parametric oscillator; PLD, pulsed laser diode; SNR, signal-to-noise ratio; TTL, transistor-transistor-logic; UST, ultrasound transducer; VIS, visible.

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Pulsed laser diodes (PLD’s) feature emitting areas as large as $800 \times 400\ \mu m^2$ and low output facet reflectivity [15], and they emit only within the NIR region. A PLD with energy output up to a few mJ has been reported using an expensive laser diode in a tomography set-up that has been shown to interrogate phantoms at depths up to 3 cm with 40–60 $\mu$m lateral resolution [16,17]. However, typical commercial PLD's provide pulse energies of only several $\mu$J and are available only in the NIR [18,19], making them suboptimal for optoacoustic mesoscopy of biological tissue, since the absorption coefficient of hemoglobin is 2–3 orders of magnitude lower in the NIR range than in the visible range. The resulting low contrast in the wavelength range of 650–1200 nm makes it difficult to image blood capillaries, a limitation that can be partially compensated by prolonging the pulse duration to 100–200 ns in order to increase the pulse energy delivered [10,18–20], but this reduces spatial resolution. To solve this issue, optical resolution optoacoustic microscopy has been achieved using pulsed diodes, but only at depths considered shallow for NIR optoacoustic imaging: one set-up achieved 1.5 $\mu$m lateral resolution and 96 $\mu$m axial resolution to a depth of 80 $\mu$m [20].

In contrast to PLD’s, continuous wave (CW) diodes can emit in the visible range, which could allow satisfactory SNR even when using lower pulse energies, due to the higher blood absorption in the visible over NIR. CW laser diodes feature small emitting areas to keep the driving current low and high output facet reflectivity to increase the efficiency [15]. In contrast to LED’s, CW laser diodes can be focused tighter and provide shorter pulse widths, making them more suitable for high-resolution imaging. Previous studies used CW laser diodes operating in pulse mode within their nominal current limits, achieving pulse energies of several nJ but necessitating coherent signal averaging over many pulses in order to increase the SNR [21–23]. As a result, a single measurement can take between 50 milliseconds at a repetition rate of 30 kHz (1500 averages) [22] and 500 milliseconds at a repetition rate of 1 kHz (512 averages) [23]. These studies used CW laser diodes only for microscopic application where lower energies per pulse are sufficient.

In this paper, we interrogated whether we could use CW laser diodes to generate more energy output per pulse and capitalize on several of their advantages, including a broader range of available wavelengths and reduced cost. We hypothesized that overdriving CW laser diodes with ultra-short current pulses can deliver stronger light pulses than when using nominal values, without damaging the diode. Therefore, our expectation was that by better matching diode emission wavelength to the absorption maximum of hemoglobin and by overdriving the diodes, we could improve SNR and resolution for imaging applications where maximizing penetration depth is not the primary goal. We developed a laser current-driver and investigated the pulse output characteristics and the longevity of CW laser diodes emitting in the visible and NIR range under different pulsed current conditions. Using laser diode overdriving, we performed raster-scanning mesoscopy of phantoms and biological tissue *in-vivo*. We demonstrate how it is possible to achieve much faster pulse repetition rates than previously reported in optoacoustic microscopy, opening up the possibility of using small, inexpensive CW laser diodes for fast optoacoustic applications.

## 2. Materials and methods

### 2.1. Pulsed laser diode driver

A laser-diode driver was constructed (Fig. 1a) to deliver high-current, nanosecond pulses at high repetition rates. The driver design is a modified and simplified version of a driver developed for laser radar applications [24]. The working principle is as follows: the capacitor $C$ is charged at high voltage $HV$ through the $R_c$ - $C$ - $D_1$ circuit. An external Transistor-Transistor-Logic (TTL) pulse triggers the power MOSFET $Q_1$ (DE275-501N16A; IXYS, USA); as the power MOSFET conducts, capacitor $C$ is discharged via laser diode $LD$. The capacitor $C$ and the power MOSFET can operate at voltages up to 500 V. Resistor $R_{CL}$ limits the current to the desired value. This design allows the current amplitude to be controlled through the high voltage amplitude. The rise time of the current pulse is determined by the turn-on speed of the power MOSFET, while the fall time is determined only by the time constant of the $R_{CL}$–$C$–$LD$–$Q_1$ circuit. Through this design, the pulse duration can be controlled by changing the capacitance value. Typical values of the components are: $R_C \cong 3.4\ \mathrm{k}\Omega$, $C \cong 400\ pF$, $R_{CL} \cong 1\ \Omega$, $R_M \cong 0.1\ \Omega$. This driver can provide the combination of very low pulse width (~<10 ns), high current (~<50–60 A) and high repetition rate (~>500 kHz), which commercially available laser diode drivers do not offer [25].

### 2.2. Diode characterization

We tested six laser diodes emitting in the visible and NIR region (Table 1) by pulsing them with the driver presented above at 50 kHz, using a function generator (33522B; Keysight, USA) to trigger the driver. The pulse peak current was adjusted by varying the high voltage from 10 to 270 V in steps of 10 V using a variable voltage supply with maximum 300 V output (EA-3050B; EA, Germany). The optical output of each laser diode was measured using a biased photodiode (DE10A/M; Thorlabs, USA) and recorded using a digital oscilloscope (DPO 7254; Tektronix, USA). The same oscilloscope was connected to the driver’s current monitor output in order to measure the peak current. Optical output measurements were averaged 1000 times, and the averages were used to determine the full-width-at-half-maximum (FWHM) optical pulse width. The mean output power was measured using a hand-held

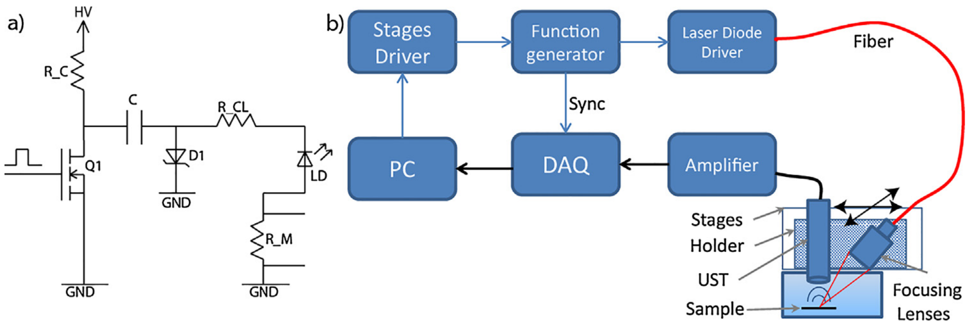

**Fig. 1.** **(a)** Schematic of the laser diode driver presented here. **(b)** Schematic of the laser diode-based optoacoustic imaging system. DAQ, data acquisition card; PC, personal computer; UST, ultrasound transducer.