DOI: 10.61782/fa.2025.0455

FORUM ACUSTICUM
EURONOISE 2025

IMPACT OF SPATIOTEMPORAL EXCITATION PARAMETERS IN LASER DIODE-BASED PHOTOACOUSTIC MICROSCOPY

Javier A. Navarro-Calvo[1*] **Irene Pi-Martín**[1] **Víctor Company-Rubio**[1]
Adrián Arándiga[1] **Alejandro Cebrecos**[1] **Juan J. García-Garrigós**[1]
[1] Instituto de Instrumentación para Imagen Molecular, Universitat Politècnica de València – Consejo Superior de Investigaciones Científicas, Valencia, Spain

ABSTRACT

Photoacoustic (PA) microscopy provides high-resolution images with optical-selective contrast at greater depths than conventional optical techniques by detecting acoustic waves generated from the absorption of pulsed light. To increase the applicability of the technique, cost-effective, compact laser diodes (LDs) have emerged as a promising alternative to expensive and bulky solid-state lasers (SSLs). Due to their low peak power, widened temporal pulses are generally used to obtain more pulse energy and achieve acceptable PA signal levels. Additionally, the multimode, low-quality beams emitted by LDs hinder the focusing capabilities, resulting in larger focal spots, i.e., lower image lateral resolutions. The generated signal characteristics will thus differ from the well-known broadband photoacoustic waves of several MHz produced by SSL-based systems. In this work, we conducted an experimental study to analyze the impact of the pulse duration, pulse shape, and focal spot size on the generated PA signals, using a laser diode-based photoacoustic microscope. The analysis shows that the pulse durations and focal spot sizes of LDs produce narrowband PA signals shifted towards lower frequencies. This is important for improving the design of efficient transducers, which will eventually allow the implementation of cost-effective photoacoustic imaging systems in clinical practice.

Keywords: *photoacoustic microscopy, laser diode, ultrasound, cost-effective, frequency spectrum*

*Corresponding author: janacal@i3m.upv.es

1. INTRODUCTION

Biomedical photoacoustic (PA) imaging combines optical and ultrasound technologies to offer high-resolution, non-invasive images with enhanced penetration and contrast. It relies on the photoacoustic effect, where endogenous chromophores such as melanin or haemoglobin absorb laser pulses, generating ultrasound waves that can be detected and used to reconstruct the absorption distribution [1].
The generation of PA pressure waves is based on the compliance of both stress and thermal confinements. This means that the excitation pulse duration must be shorter than the time that acoustic waves and heat require to travel through the excited volume [2]. Consequently, short pulses of a few nanoseconds coming from high-quality solid-state lasers (SSLs) are the preferred choice to efficiently generate PA signals. Moreover, the emitted acoustic waveform is proportional to the first derivative of the laser intensity temporal profile [2], [3]. Hence, short pulses generate sharp, bipolar pressure waves, allowing for high-contrast and high-resolution acoustic imaging [4].
The utilization of cost-effective laser diodes (LDs) in photoacoustic imaging (PAI) is gaining attention due to their affordability and compact size, which make them an attractive alternative to bulky and costly SSLs [5], [6]. However, these low-cost sources typically emit low-energy, low-quality laser beams, hindering their use in clinical-oriented systems [7]. The current drivers that pulse the LDs grant these sources with pulse tuning capabilities. For this reason, usually widened pulses are chosen to increase the per-pulse energy and, therefore, the image signal-to-noise ratio (SNR). However, longer pulses generate narrowband PA signals shifted to lower frequencies, which highly affects the image resolution [8], [9]. Moreover, stress confinement may be violated if the excited absorber is too small, reducing the generation efficiency.

Here, an experimental study has been carried out to study the impact of the pulse duration, pulse shape and source size in the generation of PA signals using a low-cost laser. With this work, we aim to offer novel and useful information about the generated frequency spectrum, which will eventually help the optimization of cost-effective PAI systems, aiding its implantation in clinical practice.

2. MATERIALS AND METHODS

2.1 Photoacoustic microscopy system

In this study, we used a custom photoacoustic microscope based on a cost-effective pulsed laser diode (905D2S3JT09X, Laser Components, Germany), which emits 235 W laser pulses at a PRF of up to 10 kHz in the NIR range (905 nm). The low-quality laser beam emitted by the PLD is reshaped and homogenized by coupling it into a multimode fiber. This fiber-coupled configuration allows to vary the focal spot size by simply placing a spatial filter, or pinhole, at the fiber output without decreasing the laser fluence or working distance. The current pulses are delivered by a pulse current driver (LDP-V 80–100, PicoLAS GmbH, Germany) controlled by a programmable pulse generator (Stemlab 125, RedPitaya). A commercial spherically focused sensor (focal length of 64 mm) made of polyvinylidene difluoride (PVdF) was aligned with the excitation in reflection mode with a 60º angle (Y-107, Sonic Concepts, USA), ensuring high sensitivity detection within 0.01-15 MHz. The detected PA waves are pre-amplified (ZFL-500LN, MiniCircuits, USA) and digitalized at a sampling rate of 150 MHz (ADQ14, Teledyne SP Devices, Sweden).

2.2 Experimental set-up

In optical-resolution photoacoustic microscopy, a tightly focused laser spot is used as the excitation beam, thus generating point-like acoustic sources. In this study, a USAF resolution target (R3L3S1P, Thorlabs, USA) made of a 120 nm-thin chromium film was used as absorber. To analyze the impact of the acoustic source size on the generated PA spectrum, tests were made without and with a 50 μm pinhole, having two focal spots of 150 and 50 μm, respectively. For each case, PA signals were acquired using laser pulse widths of 15, 35, 60, 80 and 100 ns, measured at their Full Width at Half Maximum. It is worth noting that low-cost pulse drivers usually generate asymmetric pulses with long rise times, which can affect the generated signals. To compensate for the poor SNR with shortened pulses, 5000 averages were done for fair comparison between cases.

3. RESULTS

The results are depicted in Figure 1. First (Fig. 1a), the larger source generates PA frequency spectra concentrated below 10 MHz, centered between 4-5 MHz depending on the pulse width. As expected, longer pulse widths result in less high frequency content in comparison with the shorter pulse, indicated by the 18 and 10 dB difference between the 10-15 MHz range and the main lobe, respectively. Similarly, for the smaller source of 50 μm (Fig. 1b), longer pulses generate PA signals with a reduced frequency content than the shorter ones. However, the small source size critically contributes to enlarging the bandwidth. While the 100 ns pulse generates PA signals with differences of around 10 dB in the 10-15 MHz range with respect to the main lobe, the 15 ns pulse generates a wideband signal, with differences below 6 dB in the 1-16 MHz range. In this case, the amplitude decrease beyond 15 MHz can also be influenced by the limited detection bandwidth of the ultrasound detector.

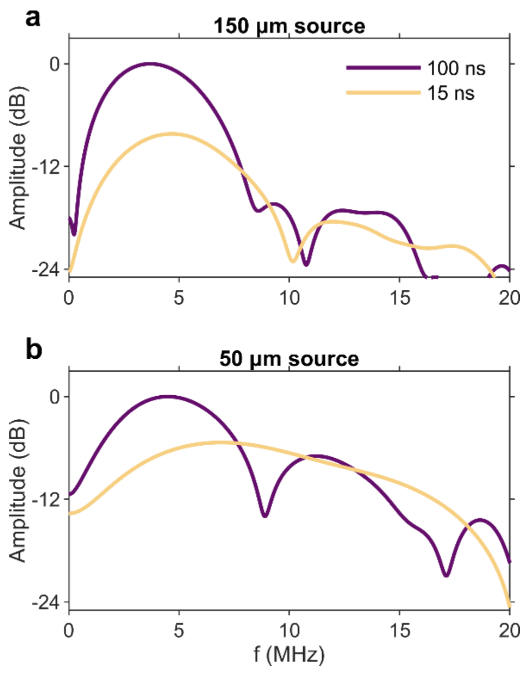

Figure 1. Comparison of the generated PA signal spectrum using pulse widths of 15 and 100 ns, for both (a) 150 μm and (b) 50 μm laser focal spots. Amplitude is normalized for each source size.

A more exhaustive analysis for all the laser pulse widths is shown in Figure 2. For the larger source of 150 μm (Fig. 2(a)), the generated PA amplitude increases with optical energy, which is proportional to the pulse width. However, for the smaller source of 50 μm (Fig. 2(b)), that trend is not observed. This discrepancy is explained by considering the confinement time, estimated to be around 33 ns for the latter. In this way, shorter pulses (60 ns) produce higher amplitude signals than wider ones (100 ns), despite having 55% less optical energy. Hence, within this range, the effects of higher PA conversion efficiency and optical energy deposition are combined.

It is noteworthy how the asymmetric laser pulse, due to the slow rise time of the low-cost current driver, induces a different PA signal morphology compared with the well-known N-shaped waveform generated with a short laser pulse with fast and symmetric flanks. In this case, the slow rise time generates a short positive lobe, followed by a sharp negative lobe coming from the fast-falling edge of the laser pulse, which highlights the influence of the selected pulse driver and the excitation pulse shape.

Regarding the generated spectrum, center frequency and bandwidth at -6 dB was calculated for each case (Fig. 2 (a, b)). As observed, both source sizes show a similar tendency, reducing the bandwidth and center frequency as the pulse size increases. However, it is visible how these variations are more noticeable for the smaller source, which shows a clearly broader spectrum for the shorter pulses.

4. CONCLUSION

An experimental study to evaluate the impact of the spatiotemporal excitation parameters (pulse width, shape, and source size) on the generated photoacoustic spectrum has been carried out. By varying the pulse width from 15 to 100 ns, with two different excitation source sizes of 150 and 50 µm, we showed that the pulse width is highly correlated with the generated PA spectrum, and that this impact is also strongly dependent on the excited absorber size, i.e., the laser spot size in an optical-resolution photoacoustic microscopy system as the one used in this study. The experimental spectra show how typical LD excitation generates narrower bandwidths, shifted to central frequencies around 5 to 10 MHz, which highly differs from the PA signals generated with high-quality SSLs. Moreover, we have provided experimental evidence of the stress confinement time violation, indicated by the reduced amplitude of PA signals generated with longer pulse widths that, despite having more energy, result in a less efficient conversion. These results show the relevance of considering both the source size and the pulse width for selecting an appropriate detection bandwidth. Also, they highlight the necessary compromise between optical pulse energy and conversion efficiency in LD-based photoacoustic microscopy systems, associated with a plausible violation of the stress confinement time.

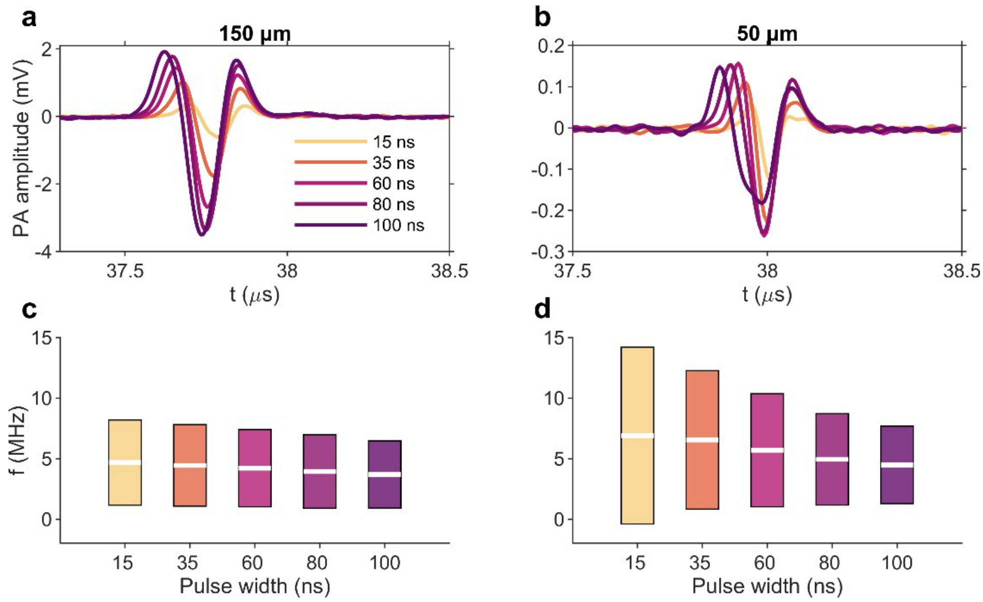

Figure 2. Experimental PA signals and their frequency content spread (center frequency and bandwidth at -6 dB) using laser pulse widths from 15 to 100 ns, for laser spots of 150 µm (a,c) and 50 µm (b,d).

We believe that these findings can provide useful insights to develop optimized PAI systems using low-cost components, thereby facilitating their integration into clinical practice.

ACKNOWLEDGEMENTS

We are grateful for the funding support through competitive call programs: Agència Valenciana de la Innovació (AVI) through the INNVA1/2022/50 project, Investigo INVEST/2022/171 Program of the European Union Next Generation EU funds.

REFERENCES

[1] J. Yao and L. V. Wang: "Sensitivity of photoacoustic microscopy", *Photoacoustics*, vol. 2, no. 2, pp. 87-101, 2014.

[2] L. V. Wang: *Photoacoustic Imaging and Spectroscopy*. Boca Raton: CRC Press, 2009.

[3] M. Pérez-Liva *et al.*: "Dual photoacoustic / ultrasound technologies for preclinical research: current status and future trends", *Phys Med Biol*, vol. 70, no. 7, p. 07TR01, 2025.

[4] P. Beard: "Biomedical photoacoustic imaging", *Interface focus*, vol. 1, no. 4, pp. 602-631, 2011.

[5] P. Kalitsounakis, G. Zacharakis, and G. J. Tserevelakis: "Towards affordable biomedical imaging: Recent advances in low-cost, high-resolution optoacoustic microscopy", *John Wiley and Sons Inc*., vol. 298, no. 1, pp. 3-9, 2024.

[6] B. Huang and T. T. W. Wong: "Review of low-cost light sources and miniaturized designs in photoacoustic microscopy", *J Biomed Opt*, vol. 29, no. S1, 2023.

[7] J. J. García-Garrigós, A. Cebrecos, J. A. Navarro-Calvo, and F. Camarena: "A fiber-coupled laser diode design for reflection mode optical resolution photoacoustic microscopy", *Ultrasonics*, vol. 132, pp. 107008, 2023.

[8] P. K. Upputuri and M. Pramanik: "Pulsed laser diode based optoacoustic imaging of biological tissues", *Biomed Phys Eng Express*, vol. 1, no. 4, p. 045010, 2015.

[9] T. A. K. Agano: "Effect of light pulse width on frequency characteristics of photoacoustic signal - an experimental study using a pulse-width tunable LED-based photoacoustic system", *International Journal of Engineering and Technology(UAE)*, vol. 7, no. 4, pp. 3835–3842, 2018.