Laser Diode Beam Shaping and Homogenization with a Multimode Fiber applied to Optical Resolution Photoacoustic Microscopy based on Linear Phased Array Ultrasound Probe

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***Abstract*—Pulsed Laser diodes stacks (PLD) are a promising low cost option as laser sources for Optical Resolution Photoacoustic Microscopes (ORPAM). Nevertheless, their multimode beams with wide divergences and non-uniform light distributions, imposes limitations to the lateral resolution that can be achieved at a long laser focusing distance needed for clinical applications. Here, it is devised a new strategy to attain high lateral resolutions at a centimeter-long working distance, based on coupling the PLD power into a square core multimode optical fiber. An ORPAM system with an ultrasound linear phased-array in reflection confocal mode was built to test its performance.**

***Index Terms*—Optical Resolution Photoacoustic Microscopy, ORPAM, Laser Diode, PLD, Linear Phased-Array, Reflection Mode**

I. Introduction

In photoacoustic (PA) imaging systems is common to choose solid state lasers (SSL), like Q-switched Nd:YAG, as the optical excitation source due to their superior performance in generating nanosecond pulse beams with high energy and high quality. These Gaussian beams are close to the diffraction limit meaning that they can be easily focused into the smallest possible spot sizes at long focal lengths and with low energy losses. Examples of these PAM systems which normally use simple optical lenses, complex microscope objectives and single- or multi-mode optical fibers, can be found in [1], [2]. Their high cost and bulky size fostered the use of semiconductor pulsed laser diodes (PLD) as a feasible alternative for optical resolution photoacoustic microscopy (ORPAM). In this imaging modality, the laser beam is focused into a small spot that, essentially, defines the lateral resolution, and requires less laser energy per pulse (few micro-Joules) in order to produce PA waves detectable by conventional ultrasound transducers. PLDs are roughly hundred times cheaper and also can achieve higher pulse repetition rates above 10 kHz, as compared to SSLs. However, the PLD beams are much more difficult to focus into small and uniform spots than pure Gaussian beams, due to their large emitting area, non-uniform fluence patterns and wide elliptical divergences, which eventually limits the system lateral resolution and PA image quality. In order to obtain smaller laser spots, it is common to use lenses of high numerical aperture (NA) and short focal lengths, or also expensive microscope objectives. These kind of optical configurations achieve good lateral resolutions, although at the cost of decreasing the laser working distance (WD) down to few millimeters [3], [4], so that there is not enough clearance for transducers, or ultrasound reflectors, to receive the wavefronts in reflection confocal mode. Two interesting optical strategies was proposed before with this aim. The first system uses a powerful 350 W PLD and a focused transducer in transmission mode, where the beam optics is made of several cylindrical lenses to prepare the beam for laser scanning with galvanometric mirrors and a final aspheric focusing lens of around 1 cm WD, claiming a lateral resolution of 21 μm [6]. A more recent system [5] is based on a 2 W visible laser diode focused with a reflective mirror objective and a spherical focusing lens, which claims a 2.2 cm WD and 10 μm lateral resolution, also with a single-element transducer in transmission mode.

In this work it is proposed a new strategy to improve lateral resolution while keeping a centimeter-long WD, so it can be used as a suitable solution to work in reflection confocal mode for ORPAM systems based on low-cost PLDs, as required for clinical applications. The optical configuration is based on coupling the PLD beam power to a multimode optical fiber of high NA and squared core, where the beam is very well homogenized at the fiber end. The fiber output will then act as a secondary laser source, now having the size and shape of the fiber core, a flat-top fluence profile and equal horizontal and vertical divergences. Afterwards, the beam is delivered to the final laser excitation point by proper imaging optics to obtain a focal spot size proportional to the fiber core.Furthermore, a higher lateral resolution is achieved by placing a pinhole aperture just at the fiber output, as a spatial filter that will

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reduce the final focal spot with constant fluence although with less laser energy. An experimental ORPAM system was built with this beam optics and a conventional linear phased array transducer in reflection mode, in order to assess its PA imaging performance on a test resolution target (USAF-1951) for two lateral resolution modes.

II. Methods

A. Description of the ORPAM System

The design of this ORPAM system is shown in the schematic of Fig. 1 (a). The chosen PLD laser source (905D3S3J08X, Laser Components, Germany) has an emission wavelength of 905 nm with a nominal pulse power of 195 W and deliver 100 ns pulses at 10 kHz repetition frequency (PRF). It is made up of 3 bars of 3 smaller laser diodes stacked vertically with an overall emission area of $200 \times 220\mu m^2$ and beam divergences of $25°$ and $10°$ (at half peak intensity), for the slow (x) and the fast (y) axes respectively. The first fiber-coupling stage consists of a pair of aspheric plano-convex lenses (ACL2520U-B, ACL1210U-B, Thorlabs, USA), in a common collimating-focusing configuration providing around 0.5 magnification factor, that launches the beam into the 150 µm square-core optical fiber, a 2 m long patch cable terminated with SMA905 connectors (M97L02, Thorlabs). For maximizing the beam power coupled into the fiber, a micrometic translator (CXY1A, Thorlabs) is used to precisely align the fiber input with two xy adjusting screws. The last optical stage has the same magnification factor as the first one, and delivers an almost flat-top beam from the fiber to the final focal spot of half the fiber core size around 75 µm. This corresponds to the normal resolution mode of the system. For the high resolution mode, a 10 µm thickness Al foil with a pinhole of 20 µm aperture (Edmund Optics, 52-869) is centered just in front of the fiber output facet to obtain a 10 µm laser spot focus. Finally, the acoustic wavefronts generated by the laser shots are received by an ultrasound linear array transducer (L11-5v) of 7.6 MHz center frequency and 128 piezo-electric elements, which is connected to the ultrasound acquisition platform Vantage 256™ (Verasonics, USA), where all the control and acquisition sequence events can be programmed in Matlab.

The ORPAM system is configured in reflection confocal mode, so that the US probe and the laser delivery optics are held above the imaging sample making up the microscope head structure. Thanks to the optical fiber, connected to the optical mounts of this structure (30 mm cages, Thorlabs), it can be freely placed elsewhere. A right angle high reflective mirror is inserted between the fiber collimating lens and the last objective lens, separated more than 10 cm, in the place of galvanometric mirrors forseen for a future laser scanning implementation. The US probe is attached to the objective lens tube by a 3D printed support which holds it at a tilted angle of $23°$ (with respect to the imaging plane), and at a fixed distance of 17.2 mm from the laser focal point. For raster scanning the xy horizontal image plane, the microscope head is mounted

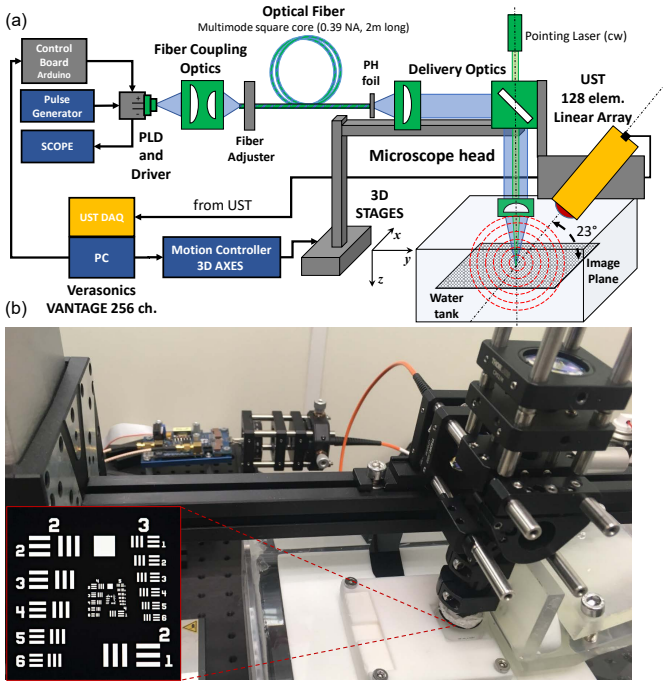


Fig. 1. The ORPAM system setup based on fiber coupled PLD laser source and linear array US probe.

onto a 3D high precision linear stages (L-511.20DG10, PI-Physik Instrumente, Germany), which are also used to adjust the laser beam focus on the imaging sample along the z vertical direction. In Fig. 1 (b) is shown the microscope head assembly and part of the experimental setup, where the 1-inch imaging test sample USAF-1951 (inset), is placed on the white platform below the microscope head immersed in a water tank.

The electronic modules and equipment of this ORPAM system are also indicated in the schematic of Fig. 1. An arbitrary function generator (R&S HMF2550) connected to the PLD current pulse driver (LDP-V 80-100, PicoLAS, Germany) is used to generate the laser pulse shots and synchronize them to the US probe acquisition time window using a TTL-level trigger signal sent from the Vantage US platform. Data acquisition of the probe RF signals and the microscope head scan motion sequences are programmed in Matlab scripts running in the same PC-based US platform. For all tests, the PRF of the PLD was set to 5 kHz and 100 ns pulse duration, at a safe 0.05% duty cycle below the 0.1% maximum rating. The pulse waveform was continuously monitored by an oscilloscope (R&S RTE1154, with 1.5GHz analog bandwidth). An Arduino control board was used to set the voltage of the PLD driver capacitors bank, and thus the PLD optical power, up to the maximum level of 65 V, while also monitoring the driver operation settings and temperature.

B. Data Acquisition and Processing of PA Images

The microscope head, with the laser focal point and the US linear probe at fixed relative position, is scanned across the xy imaging plane points at steps shorter than the laser spot size, so that they represent the pixels of the final PA image. A fixed-focus beamforming is thus performed so that all the

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linear array elements will act like a single-element focused transducer. For obtaining each image pixel, corresponding to the point-like PA source, the spherical acoustic wavefront received by the US probe is first integrated with the Delay-and-Sum (DAS) algorithm applied to the acquired RF signals of the 128 linear array elements. Before applying the DAS processing, the received signals were averaged for a number of laser shots, as specified further on, in order to reduce the electric noise in the probe and the acquisition system. The final pixel value is obtained from the resulting DAS signal by integration, or summation, for a time window of 3 ADC-samples around its pulse maximum amplitude. A time-integrating Maximum Amplitude Projection (iMAP) method is introduced here, in contrast to the commonly applied MAP method, which only takes the peak signal sample. This method is equivalent to measure the acoustic pulse energy, and the Signal-to-Noise Ratio (SNR) is improved due to the time-averaging of the background noise of the RF bipolar signal. Thanks to the iMAP method, the PA image contrast was further enhanced for the linear array transducer.

C. Laser Beam Characterization

The laser beam profile and the pulse power were measured at several key positions while mounting the transport optics, at the PLD emitting surface, the fiber ends and the final focal spot; in order to assess the optical design performance before PA imaging tests. A CCD beam profile camera (LT665, Ophir Photonics, Israel) with VIS-NIR response and a square pixel size of 4.54 μm, was used for taking the laser beam images, in a 1-to-1 scale provided by a $2f-2f$ imaging configuration with a single lens. The micro-Joule energy pulses of the PLD beam could be measured with the following optical setup: a Czerny-Turner monochromator spectrometer (AvaSpec-ULS2048XL-EVO), with spectral range in the VIS-NIR and 1.5 nm resolution, connected by optical fiber (FC-UVIR600-1-ME) to an integrating sphere (AvaSphere-30), where all the laser light is collected at the input port of 6 mm circular aperture. This setup was calibrated by the equipment manufacturer (Avantes, the Netherlands) to measure directly the absolute irradiance spectrum, or power spectral density (in $\mu W/m^2 nm$ units), for single laser pulses (with a 10 ms time integration window and a 100 Hz laser PRF). A characteristic Gaussian spectrum was recorded, obtaining a 907 nm central wavelength and 7 nm linewidth in agreement with the PLD specifications. The laser intensity per pulse was measured by integrating the full wavelength spectrum, and, then, multiplied by the input port area of the integrating sphere to obtain the laser pulse power. This value is just multiplied again by the 100 ns pulse length to get a good estimation of the laser pulse energy. These two methods also helped during the assembly and alignment of the system optics, mainly to maximize power transmission until the final laser focal spot.

D. Photoacoustic imaging evaluation tests

There were carried out several tests for assessing the imaging performance of the experimental ORPAM system using the USAF-1951 resolution test target (R1DS1P, Thorlabs). It has several alternating bar patterns grouped in different calibrated sizes, which have a good PA response due to their thin layer of NIR light absorbing chromium. The Edge Spread Function (ESF) method was used to precisely measure the PA microscope lateral resolution for the xy directions. This method consists in making line scans of the laser spot, with steps smaller than its size, across a sharp edge that separates two regions of high PA contrast, from a non-absorbing region to a strong light absorbing one. The PA signal of each line scan follows a S-shaped curve rising as more laser spot energy goes into the high absorbing region, so that it can be fitted to a Gaussian Cumulative Distribution Function (CDF). The laser spot profile is thus revealed as a Gaussian Line Spread Function (LSF), which is obtained as the derivative of the fitted ESF data, or CDF curve, in the line scan direction. Lateral resolution was obtained for the normal and high resolution modes, the first corresponding to the fiber full core emission with a focal spot around 75 μm, and, the second, to the pinhole filtered fiber emission with 10 μm spot size. Finally, PA images of several USAF target elements, each with a defined size of bars and spacing, were done to demonstrate the system imaging performance of both resolution modes.

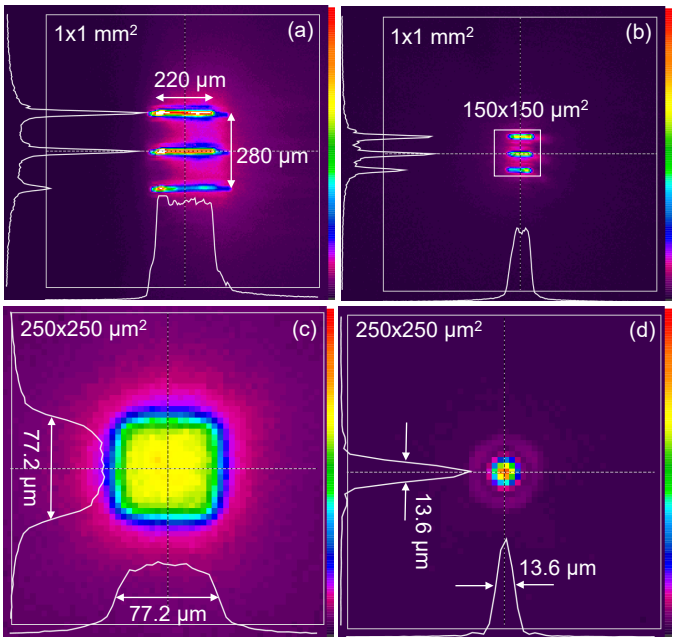


Fig. 2. Laser beam profiles of PLD (a), fiber input (b), focal spots of normal (c) and high resolution (d).

III. Results

A. PLD Beam Optical Characterization

The optical images of the laser beam cross-section in Fig. 2 show the PLD surface emission pattern with an overall size of $220 \times 280 \mu m^2$, where the vertical stack is longer than the manufacturer specification of 220 μm (a); and, how it is reduced by the fiber coupling optics down to the squared fiber core of 150 μm (b). Below in the same figure, are shown the square and circular final focal spots corresponding to the

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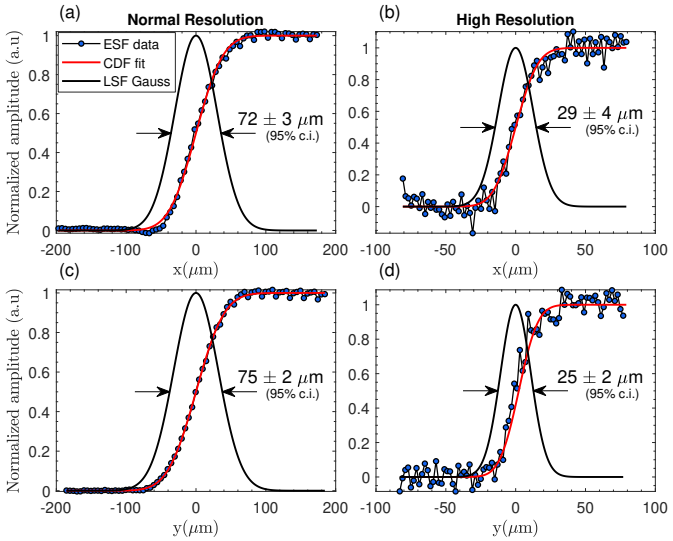


Fig. 3. Lateral resolution results with the ESF method: for normal (a,c) and high resolution (b,d) modes of the ORPAM system.

normal (c) and high resolution modes (d). Their symmetrically shaped spot sizes were measured at full-width at half-maximum (FWHM) of the fluence profiles, being 77.2 μm and 12.6 μm respectively, which are within the expected values considering the camera pixel size of 4.54 μm. A WD in air of 7 mm was determined with the same camera imaging optics, in agreement with the back focal length of the objective lens. When the objective lens tube is immersed in water during operation, the lens WD extends to 10 mm due to the refractive index of water n 1.33. This long focusing distance allowed a good ultrasound reception by the linear array transducer positioned at 17.2 mm away from the laser focus. The pulse power and energy of the laser spots for both resolution modes were measured with the spectrometer method described before, delivering 89 W / 8.9 μJ in the squared spot (c); and, 1.64 W / 0.16 μJ in the circular spot. A 1.7% of power loss due to water was also measured.

B. Lateral Resolution Measurement

In Fig. 3 are shown the experimental lateral resolution evaluated with the ESF method for both resolution modes. Each ESF data plot correspond to the average of 5 separated line scans across a test target edge, where each point was obtained by averaging the PA signal over a given number of laser shots. In the case of normal resolution (a,c), the xy lateral resolutions are 72 ± 3 μm and 75 ± 2 μm (at 95% fit confidence interval), in good agreement with the optical profile measurements. This test was done at 10 μm steps, with 4.8 μJ laser spot energy (PLD at 54 % power, 35V), and 1024 signal averaging. For the high resolution case (b,d), the lateral resolutions are 29 ± 4 μm and 25 ± 2 μm, taken with a smaller step of 2 μm, much lower spot energy of 160 nJ (PLD at full power, 65 V), and 1900 signal averaging. The oversized measure as compared to the optical spot size may be due to the low signal level close to the probe noise floor.

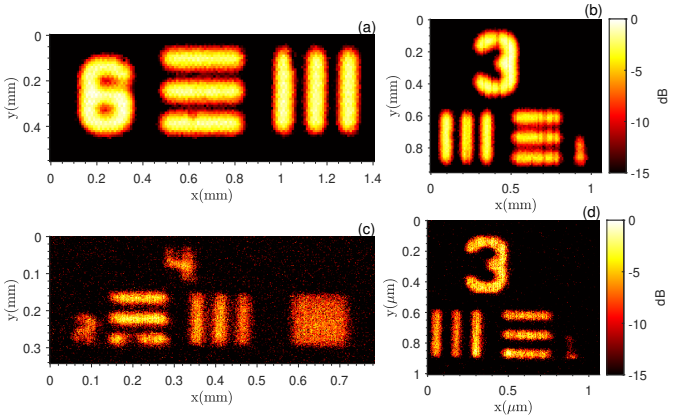


Fig. 4. USAF-1951 target PA images, normal (a,b) and high (c,d) resolution.

C. Photoacoustic images of Resolution Test Target

Normal resolution PA images of Fig. 4 (a,b) show the group 2 - element 6 of the USAF target with 70 μm of bar or spacing width, and the group 3 - element 1 of 62.5 μm bars. They were acquired for 10 μm pixel size (or scan step). A low PA signal averaging of 128 was required due to high laser energy delivered per shot of 4.8 μJ at 54 % of the PLD full optical power, with a SNR above 30 dB. The high resolution images shown in Fig. 4 (c,d) were taken at PLD full power with 160 nJ laser energy per shot, and 1900 averaging to get a SNR above 15 dB. They correspond to the group 4 - element 2 of 28 μm bars with 2 μm pixel size; and, to the same target element as in (b), now with 5 μm pixels, to directly compare both resolution modes performance.

IV. Conclusion

We have built and tested an experimental ORPAM system based on a low-cost PLD laser coupled to a square-core multimode optical fiber, which is capable of good lateral resolutions, of 75 μm at 30 dB SNR, and at least 25 μm at 15 dB SNR, both at a 1 cm long working distance. These figures are comparable to the best reported PLD-based ORPAM systems, and is the first time obtained in reflection confocal mode and with a conventional linear phased-array. Therefore, the proposed optical configuration could be used with higher sensitivity focused US receiver and fast laser scanning as a good candidate foe a clinical class device.

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