Detection of Laser-Induced Underwater Optoacoustic Signals Using Commercial Piezoelectric Sensors

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This work focuses on experimental characterization of underwater ultrasonic waves generated by high-intensity nanosecond laser pulses using two piezoelectric sensors. A pulsed laser delivering 100 mJ per pulse with a duration of 10 ns was focused into a water tank to drive a laser-induced shock wave. The resulting laser–water interaction produced acoustic transients, which were captured using a polyvinylidene fluoride (PVDF) polymer film sensor as well as a piezo sounder disc for comparison. The time-domain response of PVDF-film's observations revealed a sharp bipolar waveform lasting approximately 5 microseconds peak-to-peak, followed by multiple reflections consistent with the tank boundaries. This study delivers a qualitative comparative analysis that lays the groundwork for subsequent calibrated pressure characterization.

When high-intensity laser pulses are focused into a fluid medium, rapid localized heating leads to the emission of ultrasonic pressure waves. This process, known as the photoacoustic (or optoacoustic) effect, allows for the noncontact generation of sound using light. It finds applications in biomedical imaging, materials science, and underwater acoustics.

In water, the absorption of nanosecond-scale laser energy produces ultrasonic pulses through thermoelastic expansion and, at higher energies, cavitation. Detecting these signals provides insight into laser–matter interactions and enables precise, localized acoustic sources.

In this study, we focus nanosecond laser pulses into a water tank and detect the resulting ultrasonic signals using a polyvinylidene fluoride (PVDF) piezoelectric films and piezoelectric sounder discs. The signals are recorded without amplification using a mixed signal oscilloscope. Time-domain analysis is consistent with thermoelastic photoacoustic generation reported in literature. The experimental results were consistent with the previously reported waveform characteristics. This work is intended as an applied, qualitative investigation suitable for low-cost experimental platforms, rather than a precision acoustic study.

While laser-induced optoacoustic signals in water have been extensively studied using calibrated hydrophones, fewer reports explore the qualitative fidelity achievable using low-cost, commercially available piezoelectric sensors without amplification. This work demonstrates that PVDF polymer films can reproducibly capture characteristic bipolar optoacoustic signatures under nanosecond laser excitation, providing a viable platform for low-cost experimental and educational investigations.

I. THEORETICAL BACKGROUND

A. General Description of the Piezoelectric Effect

Certain crystalline and ceramic materials possess the ability to convert the applied mechanical stress and/or vibrations into potential difference and vice versa.

In practical sensing applications, including the present work, the inverse piezoelectric effect is not considered. The discussion in the following subsection therefore focuses on the direct piezoelectric effect under dynamic stress conditions relevant to ultrasonic wave detection.

B. The Photoacoustic Effect & the Characteristics of the Acoustic Pulse

When high-intensity laser is pulsed in a medium, a fraction of the optical energy is deposited over a short timescale, leading to rapid localized heating. Transient pressure waves are created, which are generally ultrasonic in nature. This process, known as the photoacoustic or optoacoustic effect, enables the conversion of optical energy into acoustic signals. The governing mechanism is primarily thermoelastic expansion under nanosecond excitation.

In the context of focused laser excitation, the characteristic length scale L corresponds to the spatial extent of the laser-initially heated region in the medium. For a weakly absorbing medium such as water at 532 nm, this length scale is primarily determined by the optical focal spot size rather than the optical absorption depth.

For a Gaussian beam, the beam waist w_0 at the focus is given by[1]:

$$w_0 \approx \frac{f\lambda}{\pi w_{\mathrm{in}} \mu_{water}} \tag{1}$$

assuming a near-Gaussian beam profile, where f is the focal length of the lens, λ is the laser wavelength, $\mu_{water} \approx 1.33$, and w_{in} is the radius of the incident beam at the lens. In the present experiment, we will take the smallest dimension of the heated volume to dominate stress relaxation. This yields a focal spot radius on the order of $w_0 \sim 10$–$20\ \mu$m. Accordingly, the characteristic acoustic transit time across the heated region is

$$\tau_s = \frac{L}{c_s} \approx \frac{w_0}{c_s} \sim 7\text{–}13 \text{ ns}. \tag{2}$$

This estimate is order-of-magnitude and intended solely to motivate the timescale comparison, not as a precise optical characterization.

Since the laser pulse duration ($\tau_L = 10$ ns) is comparable to the acoustic transit time, but does not satisfy the stress confinement condition[2] $\tau_L << \tau_s$, the experiment operates in a *partial stress confinement regime*. Under such conditions, a bipolar optoacoustic pressure transient is still generated, although the intrinsic nanosecond-scale source waveform is broadened in the experimentally detected signal due to finite detector bandwidth and impulse response effects.

Previous studies employing calibrated hydrophones have reported bipolar ultrasonic pressure waveforms following nanosecond laser excitation in water. A representative example from literature is shown in the following figures, illustrating the characteristic temporal profile and bandwidth of laser-induced optoacoustic signals.

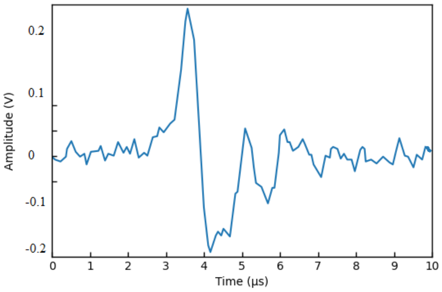

FIG. 1. Redrawn from 2022 Brelet *et al.*[3]; not reproduced verbatim. Representative optoacoustic waveform reported in literature for femtosecond laser LF response of calibrated hydrophones underwater.

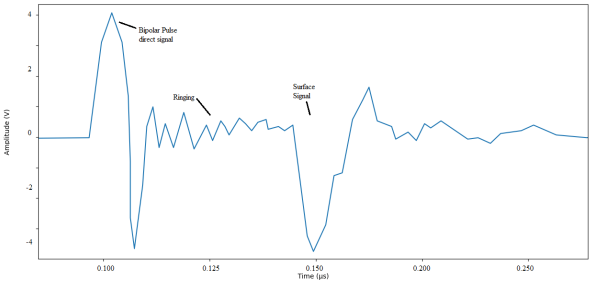

FIG. 2. Redrawn from 2020 Barmark *et al.*[4]; not reproduced verbatim. A sample waveform generated by the averaging of 256 laser pulses of 51.1 mJ acquired by the thermoacoustic sensor.

C. Piezoelectric Sensors for Wave Detection

The piezoelectric effect is widely used in ultrasonic sensing as sensors can respond to dynamic mechanical stress, like pressure waves. This detection is generally performed in voltage-mode or current-mode. In the following experiment we have worked with a commercial piezo sounder disc (27mm diameter, 3mm thickness) as well as a PVDF piezo polymer film (LDT1-028K) in voltage-mode, as they were directly connected to the oscilloscope without any pre-amp, enabling qualitative comparison of time-domain waveform fidelity.

Piezoelectric sensors do not directly measure acoustic pressure as a function of time. Instead, the incident pressure transient is converted into a voltage signal governed by the electromechanical response of the sensor and associated electronics. The measured voltage waveform can be expressed as the convolution

$$V(t) = p(t) * h(t), \tag{3}$$

where $p(t)$ is the incident acoustic pressure and $h(t)$ is the impulse response of the piezoelectric sensing system[2].

For thin piezoelectric films and discs, the impulse response $h(t)$ is determined by mechanical resonance, acoustic loading, and electrical termination, resulting in a band-limited response with microsecond-scale ring-down. Consequently, impulsive or short-duration pressure excitation produces a time-stretched voltage waveform whose temporal extent reflects the detector response rather than the intrinsic source duration.

Because the piezoelectric sensing system is linear, the bipolar nature of a thermoelastic optoacoustic pressure transient is preserved under convolution, even though the waveform is temporally broadened[24].

Commercial piezoelectric ceramic discs are typically designed for primary resonant operations in the kilohertz range, as specified in manufacturer datasheets, and are commonly employed as buzzers or narrowband acoustic transducers. Due to their high mechanical Q and resonant design, such ceramic discs exhibit prolonged ring-down and distorted impulse responses when exposed to broadband ultrasonic transients.

Polyvinylidene Fluoride (PVDF) polymer films have been extensively investigated as broadband ultrasonic sensing elements for in-air[5] as well as underwater applications. Owing to their low mechanical quality factor, high intrinsic damping, and acoustic impedance closer to air compared to piezoceramics, PVDF sensors exhibit reduced ringing and enhanced sensitivity to transient ultrasonic pressure waves. These properties make PVDF especially well suited for impulsive, broadband ultrasonic signals, where accurate temporal response and wide frequency coverage are critical. The thin-film geometry and compliant mechanical nature of PVDF further enable fast response times and effective airborne coupling, positioning PVDF as a mature and reliable material choice for broadband ultrasonic detection. For impulsive, broadband ultrasonic signals generated by nanosecond laser excitation, low-Q piezoelectric polymer sensors such as PVDF offer a favorable balance between bandwidth, sensitivity, and mechanical damping[5].

II. EXPERIMENTAL SETUP & METHODOLOGY

A. Laser System

A pulsed Nd:YAG laser operating at a wavelength of 532 nm was used to generate photoacoustic signals in water. The pulse duration was in the nanosecond regime, delivering approximately 100 mJ per pulse. The laser operated at a repetition rate of 1–2 Hz across different experiments. The beam was directed horizontally towards the tank and passed through a biconvex focusing lens before entering the water. The lens had a nominal focal length of 15 cm in air. While the optical properties of water reduce the effective focal length, this was not quantitatively calibrated in the present setup.

B. Water Tank and Optical Arrangement & Sensors

The experiments were conducted in a glass tank with top-view dimensions of 29.2 cm × 22.7 cm. The laser beam was introduced through the front wall of the tank after passing through the external focusing lens. The focal spot occurred 14.2 cm below the water surface, visible as a high-intensity luminous region. Due to the brightness, visual confirmation required the use of protective laser safety goggles. The biconvex lens was mounted outside the tank, and the laser beam passed sequentially through air, lens, glass, and then water before reaching the focal region.

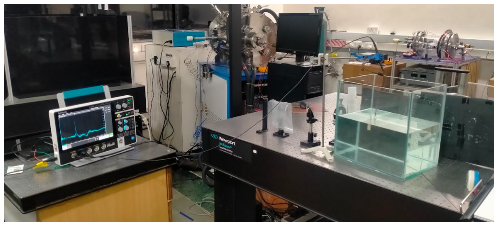

FIG. 3. View of the laboratory setup while conducting the experiment

First a commercial piezoelectric ceramic disc was covered in silicone gel evenly and then fully submerged in water facing the focal point. Once the observations were recorded, the disc was replaced with an LDT1-028k PVDF-film, which was fully submerged in the tank (the terminals were coated with silicone gel in order to make them waterproof) and positioned to directly face the beam focus at close proximity. Properties of these sensors are elaborated in the appendix.

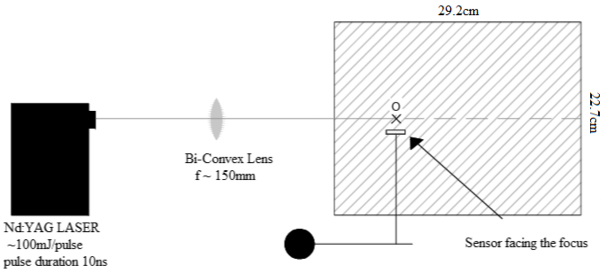

FIG. 4. Schematic of the experimental setup

C. Data Acquisition

Raw, unfiltered waveforms were recorded using the Tektronix MSO 2 Series. The laser was externally triggered on MSO, with signal averaging performed over 100 to 300 pulses per acquisition. Although individual traces showed considerable variation, averaged waveforms were clean, well-defined, and highly repeatable. The observed temporal width corresponds to the detected optoacoustic transient as shaped by the sensors' response, rather than the intrinsic thermoelastic source duration.

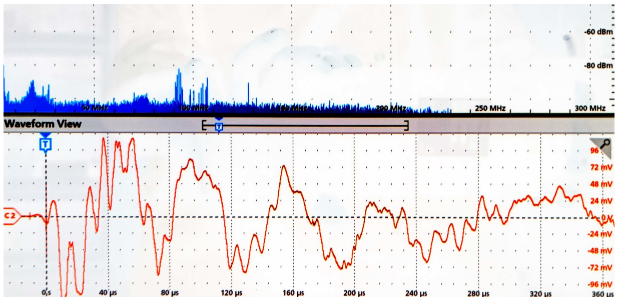

FIG. 5. Time & frequency of the averaged signal from the piezoelectric sounder disc.

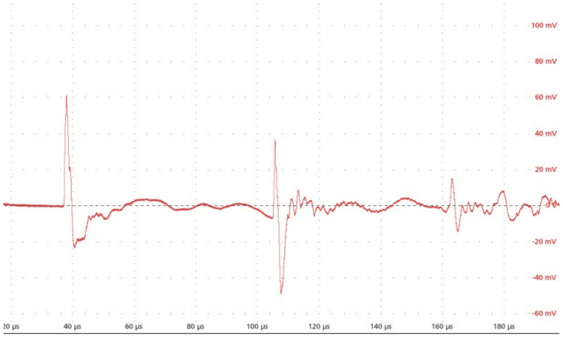

FIG. 6. Averaged acoustic waveform captured using a submerged PVDF strip following pulsed laser excitation in water.

III. RESULTS

A. Time-domain Waveforms Obtained

Both the sensors were able to detect the incoming optoacoustic signal. As anticipated, the piezo disc, due to its higher Q-factor demonstrated higher order of ringing which resulted in an inconsistent, noisy waveform, as show in the figure. However, it should be noted that even though the detection was noisy, the sensor consistently detected the waveform.

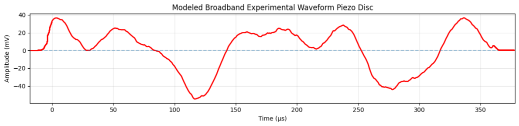

FIG. 7. Redrawn experimental waveform for piezo disc. Note the broad and noisy frequency content with weak peak definition, in contrast to the PVDF response.

Background measurements without laser firing was observed and no comparable transients were observed in the absence of laser excitation during alignment.

Meanwhile, the PVDF film was able to reproduce cleaner waveforms which were again consistent and resembled previously conducted experiments as also referenced in the figure. The original bipolar waveform lasts for approximately 5 μs and its damped reflection appears within 60-80 μs

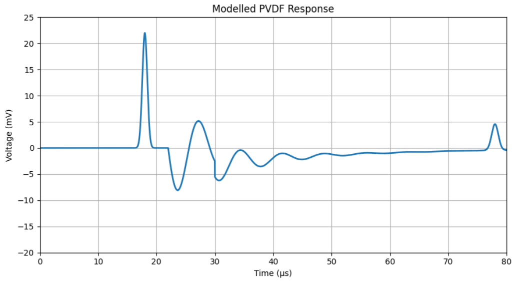

FIG. 8. Redrawn experimental waveform for a PVDF film. The primary pressure pulse is visible at the leading edge, followed by distinct reflections, likely from the tank boundaries and water–glass interfaces. This signal was averaged over 140 laser pulses to enhance signal-to-noise ratio.

B. Distance vs peak-to-peak voltage observations (PVDF)

Table I demonstrates the recorded distance of the sensor from the focus, with respect to the maximum voltage peak observations for the PVDF sensing.

TABLE I. Distance vs Max. Voltage Peak

Distance (cm)	**Max Voltage Peak (mV)**
4.0	57
3.0	60
2.0	72
1.5	120
1.0	227

This measurement is included only to demonstrate monotonic sensitivity response and positioning repeatability, not to infer propagation laws.

As shown in Table I, the detected voltage increases monotonically as the sensor is positioned closer to the laser-induced acoustic source. This trend is consistent with increased acoustic pressure amplitude in the vicinity of the focal region. Owing to the absence of absolute calibration and the influence of sensor alignment and coupling, the reported values are treated as qualitative indicators of relative signal strength rather than quantitative pressure measurements.

It should be noted that the distance is measured from estimated focal region (visual luminous region), not true acoustic source center. These values should not be interpreted as pressure decay or inverse-square behavior.

IV. INTERPRETATION

As observed in the experimental measurements, the PVDF detected optoacoustic waveforms exhibit a bipolar structure with microsecond-scale duration, despite calculations indicating a nanosecond-scale intrinsic optoacoustic source timescale based on the laser pulse duration and focal spot size.

This apparent difference is consistent with the response characteristics of the PVDF sensor employed.

The LDT1-028K piezoelectric film operates as a broadband ultrasonic detector whose impulse response extends over several microseconds. As discussed in Section I, the measured voltage waveform represents the convolution of the intrinsic pressure transient with the sensor transfer function. Accordingly, a nanosecond-scale thermoelastic optoacoustic excitation appears as a time-stretched bipolar voltage signal governed primarily by the sensor response. Similar microsecond-scale bipolar waveforms resulting from nanosecond excitation have been reported in prior thermoacoustic and optoacoustic measurements using piezoelectric detectors.

The averaged waveforms obtained using the PVDF film reveal a clear, repeatable pressure transient profile. The signal's leading edge exhibits a steep rise within a microsecond timescale, followed by oscillatory damping of optoacoustic generation via rapid energy deposition in a confined medium. The initial spike, lasting for a few microseconds, aligns with the expected detected timescale after propagation and sensor impulse response effects.

Compared to the PVDF strip, the piezoelectric disc sensor performed inadequately. Its time-domain response showed less coherence and increased ringing, likely due to resonant artifacts from its structural design. The corresponding FFT was noisy and lacked well-defined peaks, suggesting broader susceptibility to mechanical and electromagnetic interference. This contrast reinforces the PVDF sensor's superior bandwidth, acoustic matching, and temporal fidelity in capturing fast acoustic transients.

Overall, the system demonstrates the feasibility of detecting nanosecond laser-induced acoustic signatures in water using compact, high-bandwidth sensors. The observed agreement between PVDF-detected waveforms and hydrophone-reported optoacoustic signatures suggests that polymer piezoelectric sensors are well suited for qualitative time-domain studies of laser-induced ultrasound.

The primary limitations of this study include the absence of calibrated hydrophones, limited bandwidth characterization of sensors, uncertainty in optical focal volume, and reliance on signal averaging. Consequently, the results should be interpreted as qualitative rather than quantitative.

APPENDIX: EXPERIMENTAL PARAMETERS AND EQUIPMENT

- **Laser Source:** Q-switched Nd:YAG laser, wavelength 532 nm. Each pulse carried 100 mJ/pulse, each pulse with a duration of 10 ns. Experiments were performed at 1 Hz and 2 Hz repetition rates.

- **Focusing and Container Geometry:** Laser beam was focused approximately 14.2 cm above the base of the water tank. The container was a rectangular glass vessel with a top-view dimension of 29.2 cm × 22.7 cm. Water was filled up to 2-3 cm above the focal point height in order to fully submerge the sensors.

- **Detector Configuration:** Sensors were submerged in still water and positioned directly facing the laser's focal point to detect generated ultrasonic signatures. No commercial hydrophone was used. Both the sensors were used in thickness mode.

- **Data Acquisition:** Signals were acquired using a Tektronix MSO 2 Series mixed-signal oscilloscope. Averaging was performed over a variable 100-300 pulses varied depending on experimental runs.

- **Oscilloscope Settings:** Time division was set to 10 μs. Triggering was set relative to the laser source under regular mode. The MSO was set to AC coupling. Captured waveforms were stored via oscilloscope screenshots; no post-processing hardware or software was used during acquisition. Analog bandwidth and sampling rate were configured with manufacturer-default bandwidth and sampling settings.

- **Piezo Disc Characteristics:** A commercially available, generic 27 mm diameter 3mm thick piezoelectric ceramic disc bonded to a brass substrate was used.

- **PVDF Film Characteristics:** The PVDF sensor used was LDT1-028K piezoelectric polymer film with 28 μm film thickness. Minimum impedance 1MΩ.

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