

Atypical Applications for Gas-coupled Laser Acoustic Detection

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Abstract. Gas-coupled laser acoustic detection (GCLAD) was primarily developed to sense laser-generated ultrasound in composite materials. In a typical setup, a laser beam is directed parallel to the material surface. Radiated ultrasound waves deflect or displace the probe beam resulting from changes in the air's index of refraction. A position-sensitive photodetector senses the beam movement, and produces a signal proportional to the ultrasound wave. In this paper, we discuss three applications of GCLAD that take advantage of the unique detection characteristics. Directivity patterns of ultrasound amplitude in water demonstrate the use of GCLAD as a directional hydrophone. We also demonstrate the sensing of waveforms from a gelatin. The gelatin mimics ultrasound propagation through skin tissues. Lastly, we show how GCLAD can be used as a line receiver for continuous laser generation of ultrasound. CLGU may enable ultrasound scanning at rates that are orders of magnitude faster than current methods.

1. Introduction

Gas-coupled laser acoustic detection (GCLAD) was originally developed to sense laser-generated ultrasound in composite materials. [1] In a typical setup, a laser beam is directed parallel to the material surface. As ultrasound travels through the material, a portion of the waveforms traverses the solid/air interface and radiates into the surrounding air. The airborne ultrasound waves create a deflection or displacement of the probe beam [2] resulting from changes in the index of refraction. A position-sensitive photodetector senses the beam movement, producing a signal proportional to the ultrasound wave. Since the technique is independent of the optical surface properties, it has been developed as an alternative to interferometric-based detection systems for inspecting materials with optically rough or nonreflective surfaces.

GCLAD has several unique properties that may prove useful in other acoustic sensing situations. The method requires very few components, has modest laser power and stability requirements, and has a broadband frequency response. The technique can be easily modified for different situations. Here we report on progress on three atypical applications of GCLAD:

- Using optical beam deflection or displacement to sense ultrasound in water.
- Sensing ultrasound transmitted through gelatins.
- Using GCLAD as a line receiver for detecting waveforms generated by Continuous Laser Generation of Ultrasound (CLGU). [3, 4, 5]



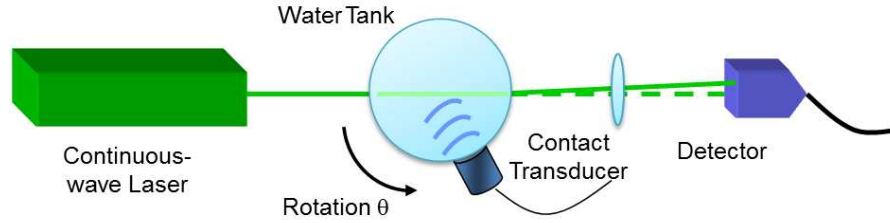


Figure 1. Experimental arrangement for the measurement of ultrasound directivity dependence in water.

2. Underwater Acoustic Detection

In recent research, [6, 7] laser-generated ultrasound has been created in water tanks and open water by creating an underwater plasma. When a laser pulse of sufficient energy enters the water, the pulse of light self-focuses, igniting a plasma. The expansion of the water as a result of the plasma produces the ultrasound. Acoustic waves with frequencies around 30 kHz were recorded in open water as far as 300 meters away with a conventional hydrophone.

In place of a conventional hydrophone, a laser-based detection system could be used to create a complete laser-based ultrasound system. A GCLAD-like detection method could have advantages over hydrophone detection, such as directivity, frequency range, and cost. In this paper, we report measurements of the directivity response of GCLAD for underwater ultrasound. If we can show that the directional dependence is strong in comparison to current directional hydrophones, this technique could be used as a highly sensitive directional hydrophone.

Figure 1 shows the experimental arrangement. A 1 MHz contact transducer was put in contact with a cylindrical tank filled with tap water. The polyethylene terephthalate (PET) tank is transparent to visible light and has a diameter of 22 centimeters. The tank was positioned on a rotation stage, allowing the transducer to be rotated along with the tank. A laser beam was directed through the tank such that it would encounter the ultrasound in the center of the

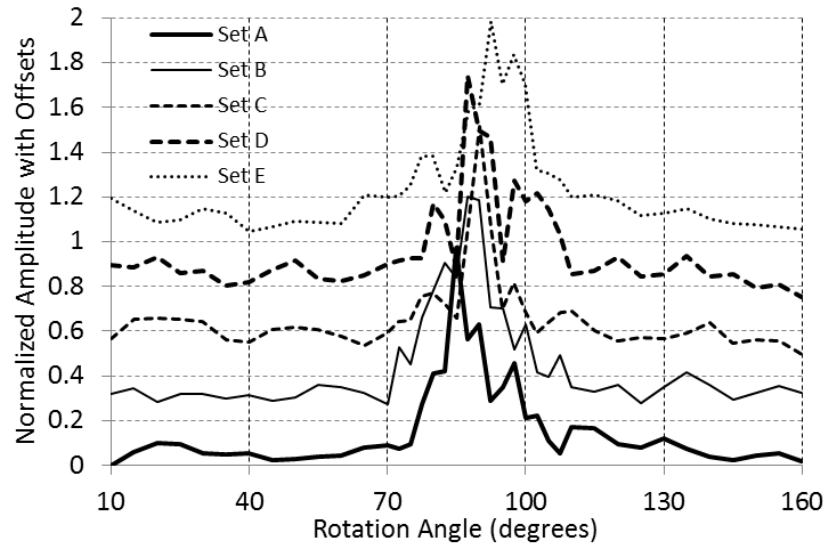


Figure 2. Directivity patterns for several experimental runs. Offsets were added to the data to better show the shifts of the central peak.

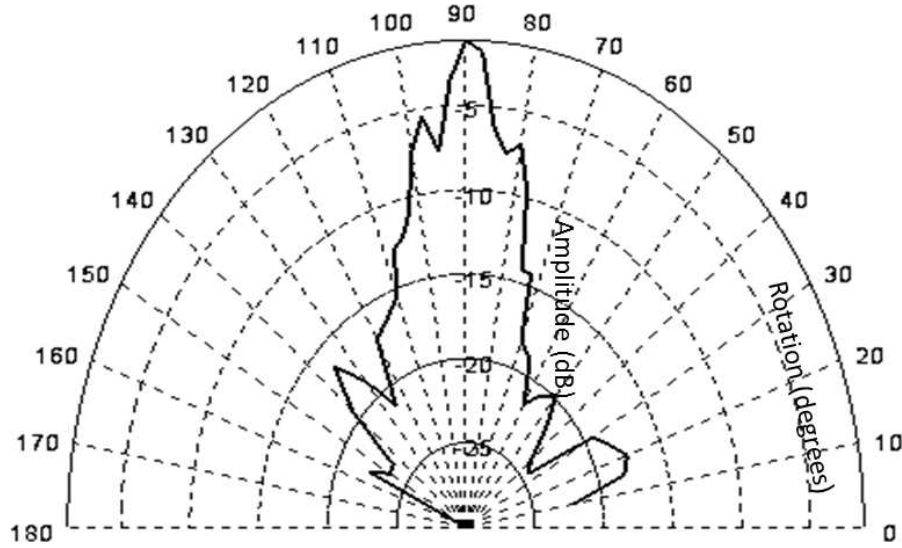


Figure 3. Polar plot for the average of four directivity tests.

tank and received through a lens by the position-sensitive detector. The placement of the lens, which is critical to achieve optimum sensitivity, was calculated using the method described in Caron. [8]

To form a directivity pattern, waveforms are captured for each angle. The peak-to-peak amplitude is taken from the first arrival of the longitudinal wave and plotted as a function of angle. Figure 2 shows the results of several experimental runs. The waveform is highly directional, with the majority of acoustic energy occurring within 20 degrees of the normal direction. A common figure of merit is to measure the width of the directivity pattern at half the maximum power. For the displayed runs, the range of “degrees at half power points” varies from ± 2.9 to 7.3 degrees and average to ± 5.4 degrees. For comparison, the Model DH-4 Directional Hydrophone, produced by Sonotronics, [9] specifies ± 6 degrees at half power points, however there was no information provided about the ultrasound frequency.

The shifts in the central peak shown in Figure 2 are most likely produced by day-to-day shifts in the experimental apparatus that occur when, for example, new couplant was placed on the transducer. To produce an average, the curves were shifted by degrees according to the location of their centroid. The average directivity pattern is shown in Figure 3 as a polar plot. The averaged curve shows a value of ± 5.9 degrees at half power points.

3. Laser-based Detection of Ultrasound in Gelatins

When studying anomalies in skin tissues, a thick gelatin can be used in place of the tissue for laboratory research. [10] These gelatins are created inexpensively and embedded with foreign objects to mimic different skin tissues and conditions. Various techniques have been used to generate and detect ultrasound in gelatinous materials. Generation is typically accomplished using a contact transducer or an array of transducers, but there has been research with laser generation as well. [11, 12] To sense the ultrasound, contact transducers are commonly used, but research has been performed with noncontact methods, such as noncontact piezoelectric transducers, [13] and interferometers. [14, 15]. A noncontact method may be preferable to contact transducers in situations where couplant cannot be applied, as is the case with severe burns.

Compared to the methods listed above, GCLAD has a much broader frequency response than standard piezoelectric transducers, and is less complicated to implement than an interferometer-

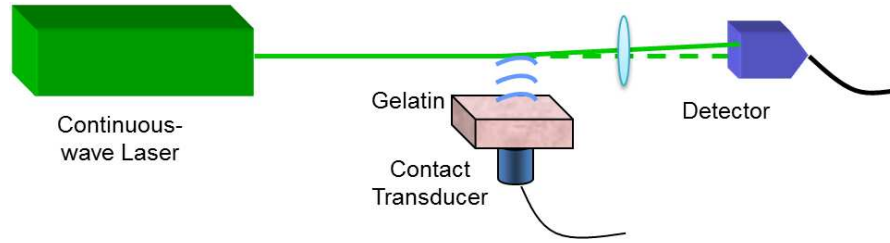


Figure 4. Laser Ultrasound Setup for sensing ultrasound in gelatins.

based system. As an initial test (based on a suggestion from a colleague [16]), a Jell-O™ brand gelatin snack pack was inserted into the GCLAD system. A 1 MHz contact transducer was used to launch the ultrasound into the approximately 5 cm thick sample, as depicted in Figure 4. The probe beam intercepts the waveform after it has radiated about an centimeter into the air on the opposite side of the transducer.

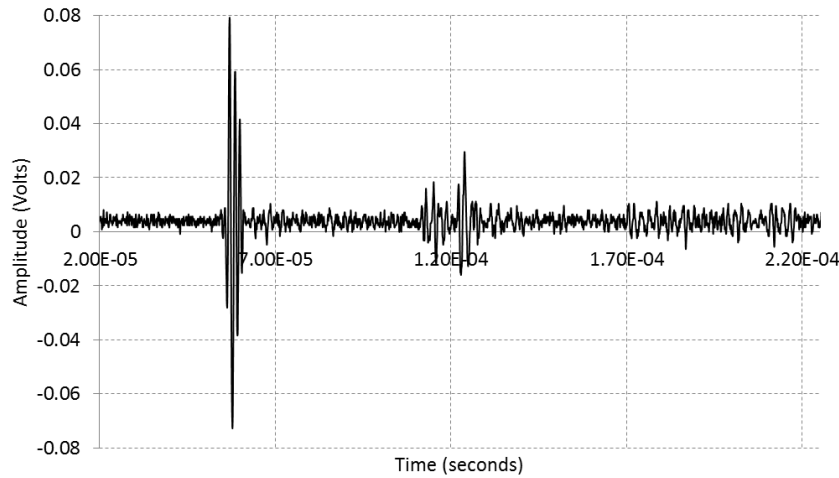


Figure 5. Longitudinal wave and the first echo in a 5 cm thick cube of Jell-O™ brand gelatin, as recorded using GCLAD.

An example of a received waveform, averaged over 16 shots is shown in Figure 5. The first arrival is clearly resolved at 55.9 microseconds and an echo can be seen at 123 microseconds. The signal-to-noise ratio, found by dividing the peak-to-peak amplitude by the standard deviation, is 102.2 with averaging or 25.6 for a single shot.

A more suitable gelatin was created using a recipe by Bude and Adler [17]. According to the authors, this type of gelatin is useful for training for in vivo biopsy procedures. The gelatin had a thickness of 3 cm, and was much firmer than our original sample. The gelatin was inserted into the setup with a 4 cm air gap between the sample and the probe beam. Figure 6 (left) shows a received waveform, averaged over 16 shots, that was generated by putting a 500 kHz pulse into a 1 MHz transducer. Based on the arrival time of $13.2 \mu\text{s}$ and the speed of sound in air, the speed of sound in the material is 1652 m/s. A Fourier frequency transform of the wave reveals a central peak at 390 kHz (right).

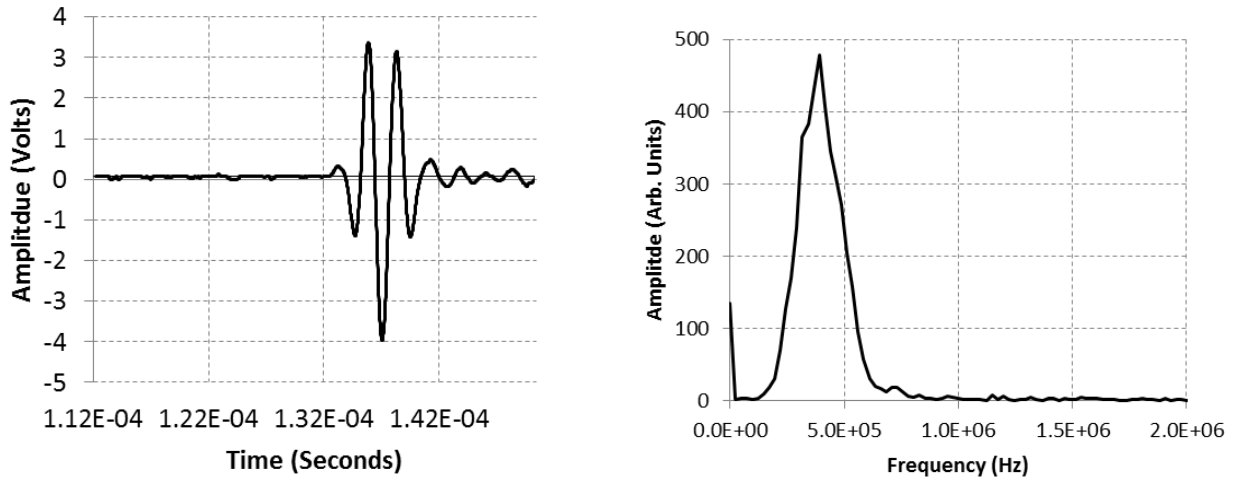


Figure 6. (Left) A longitudinal wave sensed by GCLAD after transmission through a 3 cm thick gelatin and a 4 cm air gap. (Right) An FFT of the waveform reveals a central peak at 390 kHz.

4. Line Receiver detection for CLGU

Continuous Laser Generation of Ultrasound (CLGU) has the potential to greatly increase the scanning rate of the generation of ultrasound. [4, 5] In this technique, a high power continuous wave (cw) laser beam is scanned across the surface of a material using rotating polygon mirror. The rapid deposit of energy produced by the laser produces thermoelastic expansion along the path on the surface, giving rise to an ultrasonic wavefront in the material. As with pulsed laser generation of ultrasound, sensing of this wavefront will provide information on the material's strength and the location of defects.

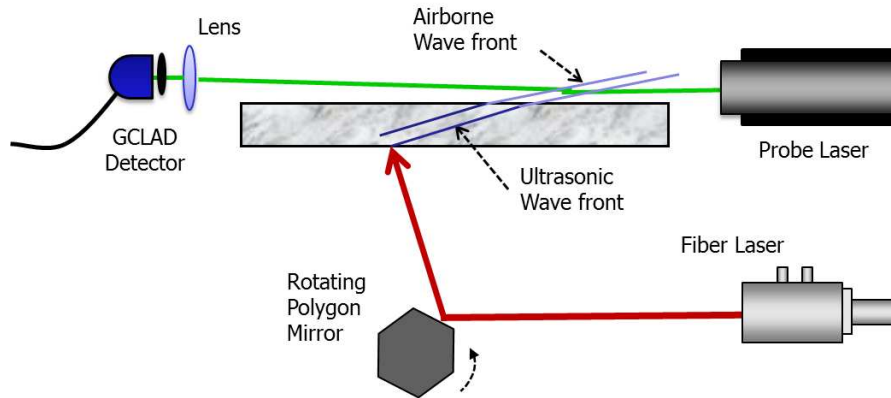


Figure 7. Concept for using GCLAD to detect ultrasound produced by CLGU. The high power cw laser, directed by a fast rotating polygon mirror, creates an ultrasonic wavefront in the material. As the wavefront reaches the solid/air boundary, a portion of the wavefront is radiated into the air and changes the path of the probe beam.

A state-of-the-art pulsed laser with adequate energy and pulse width produces 400 shots per second. To scan a meter line with millimeter resolution would take 2.5 seconds. In contrast, a CLGU system would generate a wavefront along the same line in 0.0003 seconds. The rapid

speed is necessary to deposit energy fast enough to create ultrasound in the MHz region. [5] The calculations in reference [4] show that a 10 kW cw laser with a spot size of 2 mm and a scanning rate of 3.05 km/s will produce ultrasound with a frequency of 1.52 MHz.

Detection of this wavefront is an additional challenge. An array of ultrasound transducers can be used to verify the creation of the wavefront, but would be impractical to use for a large scale system. A laser interferometer could also be created that could scan as fast as the generation. A more practical detection system can be made using GCLAD, as depicted in Figure 7. Acting as a line sensor, GCLAD can be positioned such that the probe beam runs parallel to the generation line. The ultrasonic wavefront would radiate into the air and displace the probe beam continuously. A defect in the material would create a break in the wavefront, which would upset the displacement of the beam. The timing of the upset would reveal the location of the defect.

References

- [1] Caron J N, Yang Y, Mehl J B, and Steiner K V, 2001 *Materials Evaluation*, **58**(5), p. 667.
- [2] Caron J N, 2008 *1st International Symposium on Laser Ultrasonics: Science, Technology and Applications*.
- [3] Caron J N, "Continuous laser generation of ultrasound," U.S. Patent No. 8,210,045. 3 Jul. 2012.
- [4] Caron J N, Dicom G P, and Nikitin S, 2011 *Review of Progress in QNDE*, ed D.O. Thompson and D.E. Chimenti, AIP Conference Proceedings, **1430**, p. 243.
- [5] Caron J N, Dicom G P, and Nikitin S, 2012 *Optics letters* **37**(5), p. 830.
- [6] Jones T G, Hornstein M K, Ting A C, and Wilkes Z W, 2009 *The Journal of the Acoustical Society of America*, **125**, p. 2556.
- [7] Jones T G, Helle M, Ting A C, Kaganovich D, Nicholas M, and Caron J N, 2011, Directed Energy Symposium, La Jolla, CA, p. 14.
- [8] Caron J N, 2008 *Review of Progress in QNDE*, ed D.O. Thompson and D.E. Chimenti, AIP, **27**, p.247.
- [9] SONOTRONICS, INC., 3169 S. Chrysler Avenue, Tucson, AZ 85713.
- [10] Culjat M O, Goldenberg D, Tewari P, and Singh R S, 2010 *Ultrasound in medicine and biology* **36**(6), p. 861.
- [11] Oraevsky A A, Jacques S L, and Tittel F K, 1997 *Applied Optics* **36**(1), p. 402.
- [12] Zhou S, Reynolds P, Krause R, Buma T, O'Donnell M, and Hossack J A, *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, **51**(9), p. 1178.
- [13] Kolkman R G M, Blomme E, Cool T, Bilcke M, van Leeuwen T G, Steenbergen W, Grimbergen K A, and den Heeten G J, 2010 *Journal of biomedical optics* **15**(5), p. 055011.
- [14] Rousseau G, Blouin A, and Monchalain J-P, 2012 *Biomedical optics express* **3**(1), p. 16.
- [15] Wang Y, Li C, and Wang R K, 2011 *Optics letters* **36**(20), p. 3975.
- [16] Johnson J L, 2013 "Biomedical Photoacoustic Imaging Using Gas-coupled Laser Acoustic Detection." Student Research Initiative, Boise State University.
- [17] Bude R O and Adler R S, *Journal of clinical ultrasound* **23**(4), p. 271.