DOI: 10.1177/00037028211004601

Acoustic Steering Using Thermally Induced Optical Reflection of Sound (THORS)

Journal:	*Applied Spectroscopy*
Manuscript ID	ASP-20-0399.R1
Manuscript Type:	Notes
Date Submitted by the Author:	12-Feb-2021
Complete List of Authors:	Kazal, Daniel; University of Maryland Baltimore County, Chemistry and Biochemistry Ngo, An; University of Maryland Baltimore County, Chemistry and Biochemistry Holthoff, Ellen ; Army Research Laboratory, RDRL-SEE-E Cullum, Brian ; University of Maryland Baltimore County, Chemistry and Biochemistry
Manuscript Keywords:	THORS, photothermal, acoustics, optical reflection of sound
Abstract:	Using the recently discovered THORS phenomenon, it is possible to generate optically induced, local density barriers in air by the absorption of intense, modulated laser light (the THORS phenomenon), which results in abrupt differences in compressibility of the air at these barriers that can efficiently reflect incident acoustic waves. In this note, we demonstrate the ability to optically manipulate and reflect acoustic waves in air as well as optimize the functional parameters (optical modulation and acoustic frequency) and characterize the effects of common physical parameters, including localized thermal gradients and incident angle of reflection on the efficiency of the resulting acoustic reflection. Finally, the ability to efficiently steer acoustic waves around a physical obstruction using THORS is also demonstrated.
Note: The following files were submitted by the author for peer review, but cannot be converted to PDF. You must view these files (e.g. movies) online.	
ASP-20-0399.R1_Cullum_Figures_01_to_06.zip	

Paper Type: *Notes*

Acoustic Steering Using Thermally Induced Optical Reflection of Sound (THORS)

Daniel S. Kazal[1], An Ngo[1], Ellen L. Holthoff[2], Brian M. Cullum[1]*

[1]Department of Chemistry and Biochemistry, University of Maryland Baltimore County, Baltimore, MD 21250, USA

[2] Quantum Optics & Photonics Branch, U.S. Army Research Laboratory, Adelphi, MD 20783, USA

*Corresponding author email: cullum@umbc.edu

Abstract

Using the recently discovered the thermally induced optical reflection of sound (THORS) phenomenon, it is possible to generate optically induced, local density barriers in air by the absorption of intense, modulated laser light (the THORS phenomenon), which results in abrupt differences in compressibility of the air at these barriers that can efficiently reflect incident acoustic waves. In this note, we demonstrate the ability to optically manipulate and reflect acoustic waves in air as well as optimize the functional parameters (optical modulation and acoustic frequency) and characterize the effects of common physical parameters, including localized thermal gradients and incident angle of reflection on the efficiency of the resulting acoustic reflection. Finally, the ability to efficiently steer acoustic waves around a physical obstruction using THORS is also demonstrated.

Keywords

Thermally induced optical reflection of sound, THORS, photothermal, acoustics, optical reflection of sound

<COPYEDITING/TYPESETTING>It is journal format to always place a comma after "e.g." and "i.e.", and has been changed accordingly throughout.</COPYEDITING/TYPESETTING>

<AQ>Please note: As an international scientific journal, all imperial measures include metric or SI units where needed. Please check to ensure the imperial measures were converted correctly.</AQ>

Introduction

Manipulation of acoustic waves is critical for many applications in science and engineering, including photoacoustic sensing,[1–4] sub-surface tissue imaging,[5–7] secure communications, acoustic design engineering,[8,9] and acoustic stealth technology.[10] Historically, the ability to guide and manipulate acoustic waves has typically required the use of physical material interfaces for this purpose. However, the recently discovered phenomenon known as thermally induced optical reflection of sound (THORS),[11,12] **<AQ>As noted in Manuscript Preparation FAQ URL that was provided in the preformatting request email, hyphens are removed from words ending in "-ly" because it is not journal format.</AQ>** provides the ability to generate acoustic reflective barriers by exciting media in the path of an infrared (IR) laser beam, causing abrupt changes in compressibility (and acoustic impedance) between the excited and surrounding media. Initial studies have shown that THORS barriers are capable of reflecting incident acoustic waves at efficiencies of 25% or greater. In this note, we characterize the effects functional parameters associated with the generation of THORS barriers (i.e., optical modulation and acoustic frequency) have on reflection efficiency as well as the effect localized thermal gradients and incident angle of the sound wave have on acoustic reflection efficiency of THORS barriers. Following characterization and optimization of these parameters, we demonstrate the ability to optically steer acoustic waves around physical obstructions using THORS.

Experimental

Experiments in this work were performed in an ethanol vapor environment, as show in Figure 1. A detailed description of the experimental setup for acoustic suppression and reflection measurements can be found in the paper describing the discovery of this phenomenon.[12]

<Insert Figure 1 here>

For each acoustic reflection, or suppression measurement, four datasets (with 100 averaged waves per dataset) were taken. Figure 2 shows typical signals for an acoustic suppression measurement for a THORS barrier, where the microphone measuring the fixed frequency acoustic signal is located on the opposite side of the laser beam (i.e., THORS barrier) from the earbud speaker emitting the constant tone.

<Insert Figure 2 here>

Results and Discussion

Effect of Optical Modulation and Acoustic Frequency on THORS Reflection Efficiency

Initial studies on sound reflection using THORS barriers generated in ethanol vapor, found that a minimum optical modulation frequency is required to generate efficient acoustic reflection (as well as suppression) at the barrier. In this work, we characterize the effect that the optical modulation frequency of the barrier generating laser has on acoustic reflection efficiency, as well as the effect the frequency of the incident acoustic wave (over the audible frequency spectrum; 3–10 kHz) has on THORS acoustic reflection efficiency.

Employing the experimental THORS system in the acoustic suppression mode (i.e., microphone on the opposite side of the barrier as the laser), a microphone was placed 1 mm from the edge of the laser beam. The earbud speaker was placed 9 in. (22.86 cm) away from the laser beam (i.e., THORS barrier) on the opposite side. The acoustic suppression efficiency was then measured for optical modulation frequencies of the CO_2 laser, between 0–3000 Hz for the entire audible frequency range, 3–10 kHz (in 1 kHz increments). From these studies, it was found that irrespective of the frequency of the incident acoustic wave striking the barrier, the same results were observed in terms of the effect optical modulation frequency had on suppression/reflection efficiency. Results for several incident acoustic frequencies (i.e., 4 kHz, 5 kHz, 7 kHz, and 9 kHz) covering the audible range are shown in Figure 3.

<Insert Figure 3 here>

The results from Figure 3, reveal that an optical modulation frequency of at least 600 Hz is necessary to provide acoustic suppression/reflection by a THORS barrier, but once suppression/reflection occurs, it remains constant for all higher modulation frequencies. It is hypothesized that the on/off nature of the THORS barrier suppression/reflection efficiency is related to the abruptness of the thermal barrier generated, with optical modulation frequencies below the 600 Hz cutoff, resulting in diffuse thermal gradients in the air that allow for transmission of acoustic waves, analogous to gradient refractive index materials, used for anti-reflection coatings in optics. It can also be seen, in Figure 3, that the reflection efficiency achieved, is independent of the frequency of the incident acoustic wave over the entire audible spectrum.

Localized Thermal Gradient Effects on Acoustic Reflection Efficiency

Due to the photothermal nature of the THORS phenomenon and the need to generate discreet air density differences associated with localized thermal variations, the effect of ambient air temperature on the THORS reflection/suppression efficiency was characterized. With the potential for ambient air temperatures to reach values as high as 50<thinsp>°C or greater across the globe, the ability to generate effective THORS barriers under various ambient temperatures, between 23<thinsp>°C and 53<thinsp>°C, was investigated. A Peltier heater (Laird Thermal Systems; model CP2-71-10-L1-W4.5) was used to control ambient air temperatures near the THORS barrier. The bottom of the collimated CO_2 laser beam used to generate the THORS barrier was then passed 1 mm above the surface of the Peltier heater, while the earbud speaker emitting a fixed amplitude and frequency tone (6.24 kHz) was placed on one side of the laser beam (4 in., or 10.16 cm, from the laser) and the microphone was placed 1 mm from the laser beam on the opposite side (see Fig. 4a). The ethanol reservoir was placed at the opposite end of the plexiglass chamber, so that the local heat from the Peltier heater did not alter the bulk concentration of the ethanol in the air.

<Insert Figures 4a and 4b here>

The results of these acoustic suppression efficiency studies as a function of ambient air temperature are shown in Figure 4b. As can be seen from the bar graph, at 23<thinsp>°C with an optical modulation frequency of 3000 Hz (solid dark bar), the acoustic suppression is 33% ± 4% compared to 5.3% ± 0.9% for 300 Hz optical modulation (light gray shaded bar) at 23<thinsp>°C. As expected, this acoustic suppression of approximately 30% is statistically the same as what was previously observed from the optical modulation frequency studies performed at ambient temperature. Somewhat surprisingly, as the local air temperature is raised from 23<thinsp>°C to 53<thinsp>°C, statistically equivalent acoustic suppression efficiencies are observed despite the elevated air temperature prior to the generation of the THORS barrier. At 30<thinsp>°C, 37<thinsp>°C, 47<thinsp>°C, and 53<thinsp>°C, acoustic suppression efficiency values of 31% ± 4%, 31% ± 4%, 28% ± 4%, and 32% ± 4% were observed respectively at 3000 Hz optical modulation of the CO_2 laser. Similarly, the baseline measurements (obtained at optical modulation frequencies of 300 Hz) for each of these ambient air temperatures were 3.8%

± 0.7%, 1.8% ± 0.4%, 3.7% ± 0.8%, and 5% ± 1%, respectively. These results suggest that it is possible to generate THORS barriers capable of equally reflecting/suppressing incident acoustic waves in even the most extreme natural environmental temperatures, suggesting a wide range of potential environments in which THORS can be employed with no degradation.

Effect of Acoustic Wave Incident Angle on THORS Reflection Efficiency

To redirect acoustic waves to different locations (e.g., around an obstruction), the incident angle of the propagating acoustic wave relative to a THORS barrier will need to be variable, while still effectively reflecting the incident sound wave. To this end, the reflection efficiency of sound waves as a function of incident angle on the THORS barrier was measured for angles ranging between 5° and 85°, with 90° representing orthogonal to the THORS barrier. Due to limitations associated with the size of the speaker and microphone and dimensions of the environmental chamber, angles less than 5° nor greater than 85° were capable of being measured. To perform these reflection measurements, the microphone and an earbud speaker were placed facing the THORS barrier on the same side of the CO_2 laser as seen in Figure 5a, with the angle of the speaker relative to the THORS barrier being the same as the angle between the microphone and the THORS barrier. The microphone was placed several millimeters from the beam and the speaker was placed 3 inches away from barrier to ensure the minimal distance necessary for THORS reflection exists (i.e., one acoustic wavelength).[12] The acoustic reflection efficiency of the THORS barrier was then measured for a 6.24 kHz acoustic wave at the angles of 5°, 10°, 20°, 30°, 40°, 50°, 60°, 70°, 80°, and 85° by adjusting the angle of both the speaker and microphone to matching complementary angles. These measurements were made at both 3000 Hz and 300 Hz to provide an optimized THORS barrier and a baseline measurement for each angle of incidence.

<Insert Figures 5a and 5b here>

Figure 5b, shows the acoustic reflection efficiencies for the entire range of incident angles. As can be seen from these results, at optical modulation frequencies greater than 600 Hz rate necessary to achieve THORS (solid dark bars; 3000 Hz), the same 25–30% reflection efficiency is achieved independent of the incident angle, between 5° and 85°. Additionally, as expected, at an optical modulation frequency of 300 Hz, no measurable reflection efficiency is achieved at any angle. Values of these reflection efficiencies and their respective standard deviations are reported in Table I for 3000 Hz and 300 Hz optical modulations, respectively.

<Insert Table I here>

From these values, it is clear that THORS can be used to reflect incident acoustic waves in the audible region of the spectrum with equivalent efficiency independent of the angle of incidence, allowing THORS barriers to potentially be employed to dynamically alter the acoustics of an environment.

Acoustic Steering Around a Physical Obstruction

To demonstrate the ability of THORS to optically redirect incident acoustic waves around physical barriers that would otherwise prevent the propagation of sound waves, the experimental setup shown in Figure 6a was constructed inside of the plexiglass environmental chamber in which the air was saturated with ethanol vapor, as previously described. A 3 in. (7.62 cm) thick foam block was then placed between the earbud speaker and the microphone, preventing the emitted sound from the speaker from being measurable with the microphone. To dampen the acoustic reflections in the box to minimal levels, the walls of the plexiglass environmental chamber were lined with acoustic dampening foam as well, with the exception of the optical window. The optically modulated CO_2 laser (2850 Hz modulation) was then passed through the ZnSe window of the plexiglass environmental chamber and passed by the foam block with 3 in. (7.62 cm) between them. The speaker and microphone were then aligned at a 45° angle relative to the laser beam such that any THORS reflected acoustic waves would be directed toward the microphone for measurement. To ensure that no measurable sound from the speaker could reach the microphone in the absence of a THORS barrier, the speaker was kept 5 in. (12.7 cm) from the laser beam and the microphone was held 4 in. (10.16 cm) from the laser and the amplitude of the voltage driving the speaker was reduced until the 5.71 kHz signal emitted was no longer measurable on the microphone.

<Insert Figures 6a and 6b here>

Figure 6b shows the results from a measurement in which a 5.71 kHz acoustic signal was emitted from the speaker, with the solid black trace corresponding to the signal measured by the microphone. The dotted square wave represents the optical chopper signal with a high signal corresponding to the laser not being blocked and a low signal corresponding to the laser blocked.

In addition, a dashed 5.71 kHz sine wave is overlaid for comparison to the signal measured by the microphone. As can be seen from this data, in the presence of a THORS barrier (laser on; high square wave), the signal measured by the microphone matches that of the overlaid 5.71 kHz reference sine wave, showing that the 5.71 kHz acoustic signal is being detected by the microphone. However, in the absence of the THORS barrier (laser blocked; low square wave signal), the 5.71 kHz sine wave disappears and only a weak signal corresponding to the photoacoustic background associated with the ethanol absorption of the CO_2 laser (operating at 3W) reflecting within the chamber is observed. Then as the laser turns on again (high square wave) and a THORS barrier is generated, the 5.71 kHz acoustic wave is present again with equal amplitude to the previous wave, demonstrating the ability to optically steer a significant portion of an acoustic wave around physical barriers. To verify that the 5.71 kHz signal is not simply being reflected from the walls of the chamber, the same measurement was performed with the CO_2 laser turned off and the ethanol removed, resulting in the solid baseline curve at zero acoustic amplitude.

Conclusion

Demonstration of the ability to optically redirect acoustic waves around physical barriers using THORS barriers has been shown, opening up the possibility of dynamically manipulating acoustic waves without the need for physical barriers. As long as optical modulation frequencies of greater than 600 Hz are employed by the THORS excitation laser, it is possible to reflect incident acoustic waves across the entire audible spectrum with comparable efficiency (i.e., 25–30%), thereby allowing for acoustic redirection or conversely acoustic suppression. Characterization of the physical parameters effecting the THORS phenomenon have shown that neither differences in local air temperature (between 23–53<thinsp>°C), nor differences in incident angle of the acoustic wave relative to the THORS barrier alter the reflection efficiency measurably.

Acknowledgements

The authors would thank Drs. Darren Emge and Eric Languirand of the U.S. Army Combat Capabilities Development Command, Chemical Biological Center, for loan of the ACO Pacific microphone. In addition, we would also like to gratefully acknowledge the U.S. Army Research

Office and the University of Maryland Baltimore County for funding of this work as well as the U.S. DoD SMART Fellowship program for the support of Ph.D. candidate Daniel Kazal.

References **<AQ>The references were changed to match our formatting requirements, as requested, databases, and to fill in missing information. Please check. Editor.</AQ>**

<COPYEDITING/TYPESETTING>Note the references have been formatted per ASP style. Please contact Managing Editor before making changes to format.</COPYEDITING/TYPESETTING>

1. A. Rosencwaig. "Theoretical Aspects of Photoacoustic Spectroscopy". J. Appl. Phys. 1978. 49(5): 2905–2910.
2. A. Rosencwaig. Photoacoustics and Photoacoustic Spectroscopy. New York: Wiley, 1980. **<AQ>Ref. 2 was a book review. It was changed to match the book details in WorldCat.</AQ>**
3. M.W. Sigrist. "Trace Gas Monitoring by Laser-Photoacoustic Spectroscopy". Infrared Phys. Technol. 1995. 36(1): 415–425.
4. A. A. Kosterev. "Photo-Acoustic Spectroscopy". In: M. Baudelet, editor. Laser Spectroscopy for Sensing: Fundamentals, Techniques, Applications. Amsterdam: Elsevier/Woodhead Publishing, 2014. Chap. 7, Pp. 208–234.
5. H.-J. Foth, C.G. Hoelen, F.F.M. de Mul, R. Marchesini, et al. "Nondestructive Photoacoustic Subsurface Tissue Imaging: A Feasibility Study". Proc. SPIE 2628, Optical and Imaging Techniques for Biomonitoring. 1996. doi: 10.1117/12.230000
6. S. Dahal, B.M. Cullum. "Characterization of Multiphoton Photoacoustic Spectroscopy for Subsurface Brain Tissue Diagnosis and Imaging". J. Biomed. Opt. 2016. 21(4): 047001.
7. N. Chandrasekharan, R.H. Mehta, S. Saha, B.M. Cullum. "Development of Multiphoton Photoacoustic Spectroscopy for Noninvasive Tissue Diagnostics". Proc. SPIE 5261, Smart Medical and Biomedical Sensor Technology. 2004. doi: 10.1117/12.514797
8. L. Xiao, T. Collins, Y. Sun. "Acoustic Source Localization for Design of Tangible Acoustic Interfaces". In: D.T. Pham, E.E. Eldukhri, A.J. Soroka, editors. Intelligent Production Machines and Systems. Oxford: Elsevier Science Ltd., 2006. Pp. 529–534.

9. D. Jones. "Acoustical Treatment for Indoor Areas". In: G.M. Ballou, editor. Handbook for Sound Engineers. Oxford: Focal Press, 2008. Chap. 4, Pp. 65–94.
10. P. Ball. "New Lessons for Stealth Technology". Nat. Mater. 2021. 20(1): 4.
11. D.S. Kazal, E.L. Holthoff, B.M. Cullum. "Thermally-Induced Optical Reflection of Sound (THORS) for Photoacoustic Sensing". Proc. SPIE 11020, Smart Biomedical and Physiological Sensor Technology XVI, 1102009. 2019. doi: 10.1117/12.2517971
12. B.M. Cullum, E.L. Holthoff, P.M. Pellegrino. "Optical Reflection and Waveguiding of Sound by Photo-Thermally Induced Barriers". Opt. Express. 2017. 25(19): 22738–22749.

Figure Captions

Figure 1. Experimental configuration for the measurement of acoustic suppression–reflection efficiency of THORS barriers generated in a saturated ethanol vapor environmental chamber. Exact placement of the microphone and speaker varies depending on the measurement performed, with the rest of the configuration remaining the same.

Figure 2. Typical measurement of acoustic suppression across a THORS barrier in ethanol vapor. The square wave represents the optical chopper TTL signal. The dashed sinusoidal wave is the reference signal. The solid black wave is the measured acoustic signal in the presence of a THORS barrier, showing suppression in intensity when the laser is on.

Figure 3. The acoustic suppression/reflection efficiency of acoustic waves incident on a THORS barrier, as a function of optical modulation frequency. Acoustic frequencies of (a) 4 kHz, (b) 5 kHz, (c) 7 kHz, and (d) 9 kHz are displayed. Error bars represent a standard deviation of the measurements. A sigmoidal trend line is added to demonstrate the typical off–on trend occurring at optical modulation frequencies of 600 Hz or greater.

Figure 4. (a) Experimental configuration inside the plexiglass environmental chamber, for the localized thermal gradient effects study. (b) Bar graph depicting the acoustic suppression efficiency of the THORS barrier as a function of local air temperature. Dark solid bars represent the acoustic suppression efficiency measured at an optical modulation frequency of 3000 Hz and

the light gray; shaded bars represent the acoustic suppression efficiency measured at an optical modulation frequency of 300 Hz. Error bars represent a standard deviation of the measurements.

Figure 5. (a) Configuration of experimental setup inside the plexiglass environmental chamber for the incident angle effects study. (b) Bar graph showing the acoustic reflection efficiency of sound waves incident on the THORS barrier at different angles. Solid dark bars represent the acoustic reflection efficiency for each reported angle with a 3000 Hz optical modulation frequency, and light gray (diagonal line bars) represent the reflection efficiency for each at 300 Hz optical modulation. Error bars represent a standard deviation of the measurements.

Figure 6. (a) Experimental configuration for optically redirecting acoustic waves around a physical obstruction using THORS. (b) THORS reflection of a 5.71 kHz acoustic wave around a solid barrier using THORS. The dashed square wave represents the optical chopper TTL signal with the high signal corresponding to the laser on (i.e., THORS barrier on) and the low signal corresponding to no laser present. The solid curve is the acoustic signal measured by the microphone on the other side of the barrier and the dashed curve shows an overlay of the 5.71 kHz acoustic signal being emitted from the speaker for reference. Finally, the solid baseline at zero amplitude is the microphone signal with the speaker emitting at 5.71 kHz and no laser or ethanol present.

Table I. Acoustic reflection efficiencies of sound waves incident on a THORS barrier at different incident angles. Acoustic reflection efficiencies at 3000 Hz (top). Acoustic reflection efficiencies at 300 Hz (bottom).

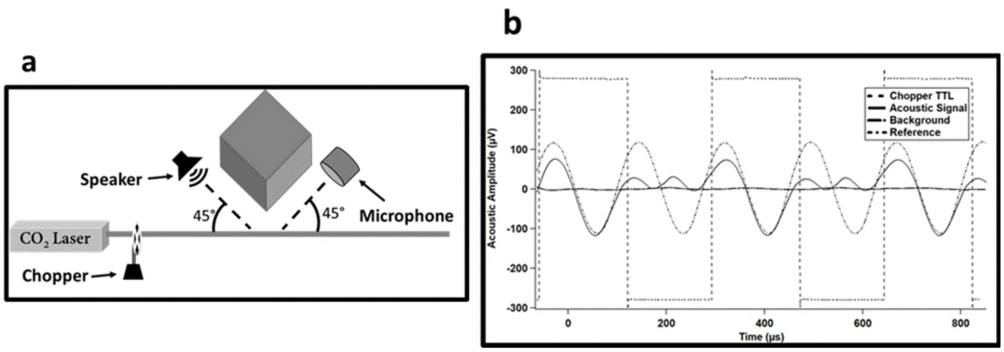
3000 Hz Optical Modulation Frequency

Angle	% Reflection	Angle (°)	% Reflection
5	30 ± 3	50	26 ± 3
10	27 ± 2	60	30 ± 2
20	27 ± 3	70	27 ± 2
30	28 ± 3	80	25 ± 2

40	27 ± 3	85	29 ± 2

300 Hz Optical Modulation Frequency

Angle	% Reflection	Angle	% Reflection
5	2 ± 1	50	3 ± 1
10	3.0 ± 0.5	60	4 ± 1
20	2 ± 1	70	2.5 ± 0.3
30	3 ± 1	80	4 ± 1
40	2 ± 1	85	2 ± 1



a) Experimental configuration, inside the plexiglass environmental chamber, demonstrating the ability to redirect acoustic waves around a physical obstruction using THORS. b) THORS reflection of a 5.71 kHz acoustic wave around a solid barrier using THORS. The dashed square wave represents the optical chopper TTL signal with the high signal corresponding to the laser (i.e., THORS barrier on) and the low signal corresponding to no laser present. The solid curve is the acoustic signal measured by the microphone on the other side of the barrier and the dotted line shows an overlay of the 5.71 kHz acoustic signal being emitted from the speaker for reference. The solid baseline at zero amplitude is the microphone signal with the speaker emitting at 5.71 kHz and no laser or ethanol present.

338x254mm (72 x 72 DPI)