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Acoustic steering of audible and ultrasonic waves using THERMALLY-induced Optical Reflection of Sound (THORS)

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ABSTRACT

The manipulation and guiding of sound waves have typically required the use of physical barriers for the reflection of an incident pressure wave. With the manipulation of acoustic waves being critical for many applications in scientific and engineering fields, including subsurface tissue imaging, photoacoustic sensing, secure communications, acoustic stealth technology, and acoustic design engineering; the requirement for physical barriers often represents a significant limitation. The recently discovered phenomenon THERMALLY-induced Optical Reflection of Sound (THORS), provides the ability to generate acoustically reflective barriers, in air, by exciting media in the path of an IR laser beam, causing abrupt changes in compressibility between the excited and surrounding media. In this work, we demonstrate the ability to efficiently reflect sound waves around physical obstructions using a laser. Additionally, this work demonstrates the ability to also manipulate ultrasonic waves via THORS barriers, where the reflection and suppression of ultrasonic pulses in the frequency range of 120-300 kHz are shown. Finally, preliminary results demonstrating the ability to employ THORS in ambient air using water vapor as the absorbing media and a 5.5 μm CO laser beam for excitation.

Keywords: Photoacoustic, THORS, Standoff sensing, Photoacoustic sensing

INTRODUCTION

The ability to manipulate acoustic waves is important to many scientific and engineering fields, including acoustic design engineering, secure communications, stealth technology, subsurface tissue imaging, and photo-acoustic sensing.¹⁻⁵ Physical barriers and interfaces are traditionally employed to achieve acoustic manipulation, where the magnitude and direction of the reflected and transmitted portions of incidents sound waves are controlled by differences in compressibility of the dissimilar acoustic transport media, and the shape of the interface (relative to the incident acoustic wave.) Although these physical barriers provide an effective and predictable means to

manipulate sound waves, they often require extensive time and effort to construct and can dramatically limit the environments in which such manipulation can be employed.

An alternative method for manipulating sound waves was discovered in the 1860's by John Tyndall.^{6,7} He showed that sound waves propagating through a flame from a Bunsen burner, were significantly attenuated in amplitude on the other side of the flame, due to the differences in air density associated with the hot air generated by the flame. Subsequent studies by Tyndall, showed that by passing an acoustic wave across a series of slotted burners substantially increased the acoustic suppression efficiency achieved, when compared to the single burner experiment. Although Tyndall's work only provided a phenomenological study of this effect, this same phenomenon has recently re-discovered using lasers instead of flames.

In recently discovered phenomenon, known as THERmally-induced optical reflection of sound (THORS) has been shown to be capable of optically manipulating acoustic waves, via thermally-induced barriers, generated by absorption of infrared laser light in gas media.⁸⁻¹⁰ THORS has been characterized, for its ability to both acoustically steer waves and guide acoustic waves down optical channels, in an ethanol vapor environment. The ability to dynamically steer and contain acoustic signals via light offers a the potential to dramatically improve many applications such as, stand-off photoacoustic spectroscopy, enhanced subsurface tissue imaging, and secure communications, by removing the need for physical acoustic barriers to manipulate sound waves.

In this work, we demonstrate the ability of THORS barriers to optically steer acoustic waves around physical obstructions, that would otherwise prevent any acoustic transmission. Additionally, the ability to generate THORS barriers in an ambient environment by utilizing atmospheric water vapor as an absorbing species following excitation at 5.5 μm by a CO laser is also demonstrated.

EXPERIMENTAL

Acoustic steering and reflection experiments were performed in an ethanol vapor environment, generated by placing an evaporation dish filled with 200 proof ethanol in a sealed plexiglass chamber (48" x 18" x 18") for at least one hour. A 3-inch, ZnSe window was mounted in a cutout at one end of the plexiglass chamber, to allow IR laser transmission into the chamber. To generate THORS barriers, a 5-Watt, CO₂ laser (Laser Photonics; Model CL55WTVO), tuned to an emission wavelength of 9.6 μm , was placed outside the chamber, passed through the center of the ZnSe window and down the length of the chamber. Optical modulation of the laser beam was performed using an optical chopper (Scitech; Model 300CD) capable of reaching modulation frequencies up to 3000 Hz. Figure 1 shows the experimental setup in the plexiglass chamber.

To quantify acoustic reflection measurements from a THORS barrier, a 0.5-inch nominal diameter, free field 0° microphone (ACO Pacific; Model No. 7046) was placed on the same side of the CO₂ laser beam as a speaker, with incident angles of the speaker and laser beam and microphone and laser beam matched to allow for monitoring of the reflected sound waves incident on the THORS barrier. The microphone output is then connected to a digital oscilloscope, to monitor the acoustic wave amplitude with respect to time. Additionally, a TTL signal from the optical chopper was coupled to the oscilloscope, to observe when the CO₂ laser was in front of the microphone as it was optically modulated. An earbud speaker (JLabs; Model J6M), placed in the chamber on the same side of the beam as the microphone, was then driven by an arbitrary function generator to emit fixed frequency sinusoidal soundwave of a known frequency.

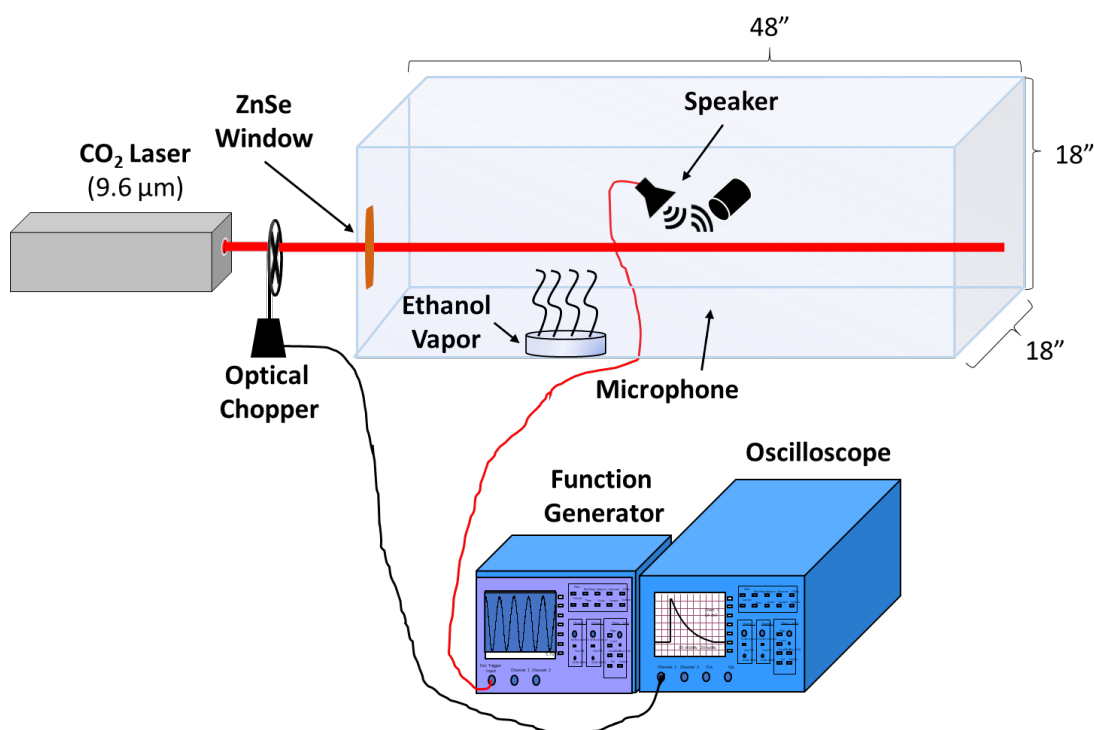


Figure 1: Experimental setup for THORS acoustic reflection measurements in an ethanol environmental chamber.

To reduce noise from the microphone signal, and allow for averaging of multiple signals, a TTL signal, equal in frequency and phase matched with the sinusoidal sound wave, was produced by a function generator and employed as an external trigger for the oscilloscope. A state trigger on the oscilloscope was set up to trigger on the positive slope of the TTL signal from the function

generator, within 1 μs of the TTL signal from the optical chopper. Subsequent acoustic data for analysis was taken by averaging 100 acquisitions on the oscilloscope.

To measure the acoustic reflection/suppression efficiency of an incident sound wave on a THORS barrier, the sound wave generated by the earbud speaker was measured with the laser shutter open (laser-on) and with it closed (reference). A photoacoustic background signal was also taken, by opening the shutter of the laser, and turning off the earbud speaker. The photoacoustic background was subtracted from the laser-on signal, in order to see the acoustic reflection. The TTL signal from the optical chopper, laser-on signal, and reference signal, were then plotted as a function of time.

As an example, Figure 2 shows suppression of a 5.7 kHz sinusoidal wave generated by the earbud speaker. These suppression measurements, are performed by placing the microphone on the opposite side of the THORS barrier than the speaker, and the resulting signal suppression measured is due to acoustic reflection off of the barrier.⁹ When observing the acoustic amplitude of the laser-on signal when the TTL signal is low (laser shutter closed) the acoustic amplitude of the signal matches that of the reference signal. As soon as the TTL signal becomes positive (laser shutter open) there is a clear decrease in acoustic amplitude by the laser-on signal of approximately 29%, when compared to the reference signal. This 29% decrease in acoustic amplitude is due to reflection of the incident sound wave off of the THORS barrier, thereby reducing the signal received by the microphone.

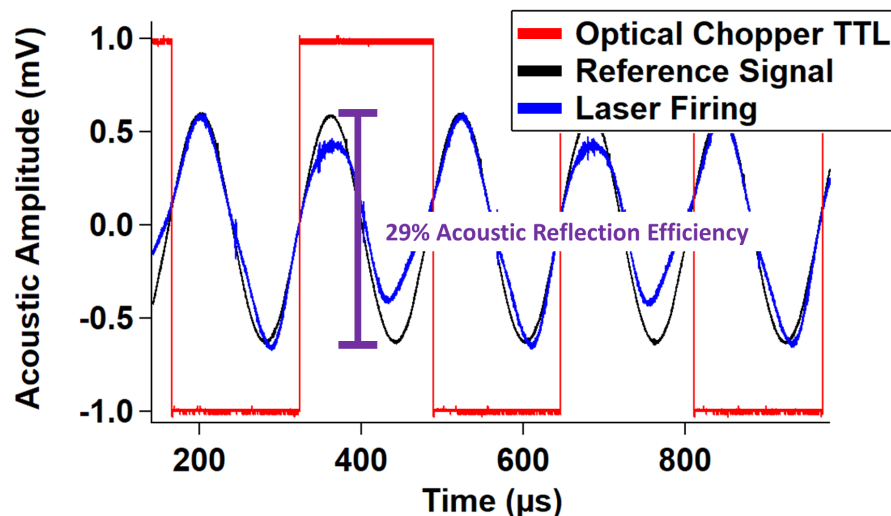


Figure 2: Example of THORS reflection/suppression efficiency measurements on an oscilloscope. The TTL signal (red) represents the laser-on, (TTL positive) and laser-off (TTL negative) timing

of the optically modulated CO₂ laser beam. The reference signal (black) of a 5.7 kHz sound wave, was acquired when the laser shutter was closed. The signal acquired when the laser was firing (blue) and the CO₂ laser shutter was open, has had the photoacoustic background signal subtracted from it.

DISCUSSION

To demonstrate the ability of THORS barrier to acoustically steer sound waves around an obstruction, that would otherwise prevent an acoustic signal from being detected, a foam block was placed between the microphone and speaker, inside the plexiglass chamber described in the experimental setup. The corner of the foam block was placed three inches away from the CO₂ laser beam, with the two sides of the foam block oriented at a 45° angle with respect to the laser beam. The earbud speaker was placed, on one side of the foam block, five inches from the laser beam, where emitted sound waves would be incidence on the THORS barrier at a 45° angle. The microphone was then placed on the opposite side of the foam block from the speaker, four inches from the beam, at a 45° angle (see Fig. 3a).

A 5.7 kHz sinusoidal wave was then emitted by the earbud speaker, where the output amplitude of the sound wave, was adjusted on the function generator, until no signal was observed by the microphone. The acoustic reflection was measured, as described in the experimental section. As seen in Figure 3b, a 5.7 kHz acoustic signal is observed when the laser shutter is open (a reference 5.7 kHz signal is overlaid in Fig. 3b for reference). As can be seen from the data, when the dotted chopper TTL signal is positive, denoting that the laser is on and generating a THORS barrier, there is a clear 5.7 kHz acoustic signal, denoted by the solid line, due to reflection off of the THORS barrier and around the foam block. When the laser turns off (chopper TTL signal low), no measurable 5.7 kHz signal is observed. While there is a minimal signal observed in the absence of laser and a THORS barrier, this is associated with photoacoustic background signals reverberating in the chamber from the absorption of the CO₂ laser by ethanol vapor. When the laser turns on again (chopper TTL high) and a THORS barrier is generated, the 5.7 kHz acoustic signal returns, equal in amplitude to the previous wave, demonstrating the ability to photo-thermally steer significant portions of an acoustic wave. To verify that the 5.71 kHz signal is not simply being reflected from the walls of the chamber, the same measurement was also performed with the CO₂ laser turned off and the ethanol removed, resulting in the solid baseline curve at zero acoustic amplitude.

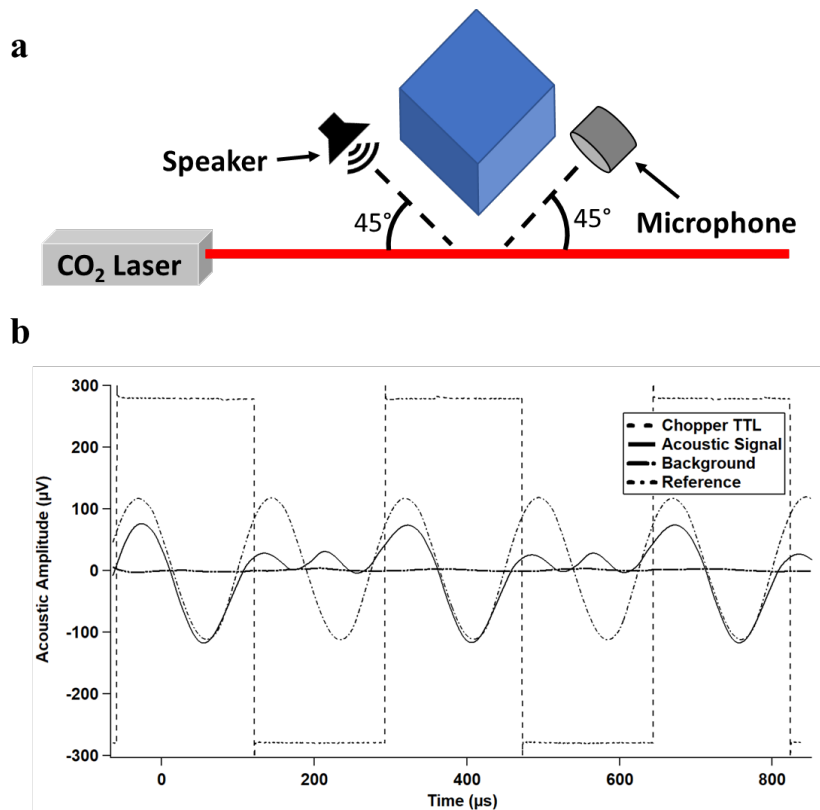


Figure 3: *a)* Experimental setup for acoustic steering around a foam-block. This simplified diagram, shows the minor modifications made to the experimental setup described in the experimental section. *b)* Acoustic reflection data, demonstrating the ability to optically steer acoustic waves around a physical obstruction. The dotted square wave represents the chopper TTL signal, where the positive signal denotes the laser firing, and the negative signal denotes the laser-off. The dotted sine wave is a reference signal generated by directly coupling the output of the function generator to the oscilloscope. The solid black wave is the acoustic signal taken when the laser shutter is open and being optically modulated. The dotted background signal is the signal produced when the laser shutter was closed, and the 5.7 kHz sine wave was emitted from the speaker.

To demonstrate the ability of THORS to be used outside of a plexiglass chamber saturated in ethanol vapor, and extend its utility to many other applications, preliminary demonstrations of THORS in ambient have also been performed. In these studies, a CO laser (Coherent; Model J-3-5) with an emission wavelength of 5.5 μm was employed as the excitation source, allowing for the optical excitation of water vapor present in the air. The CO laser is electronically modulated and can achieve optical modulation between 0 – 200 kHz with a 50% duty cycle. To test acoustic

reflection efficiency of the THORS barrier generated in ambient air without the need for an external absorbing species, two 120 kHz ultrasonic transducers, were placed orthogonally to the CO laser beam, and facing each other, with the beam passing between the transducers. Both transducers were placed three inches from the beam to ensure an acoustic wavelength of separation between them and the beam. The optical modulation frequency was set to 150 kHz, at a 50% duty cycle. The experimental setup employed for these studies is shown in Figure 4a.

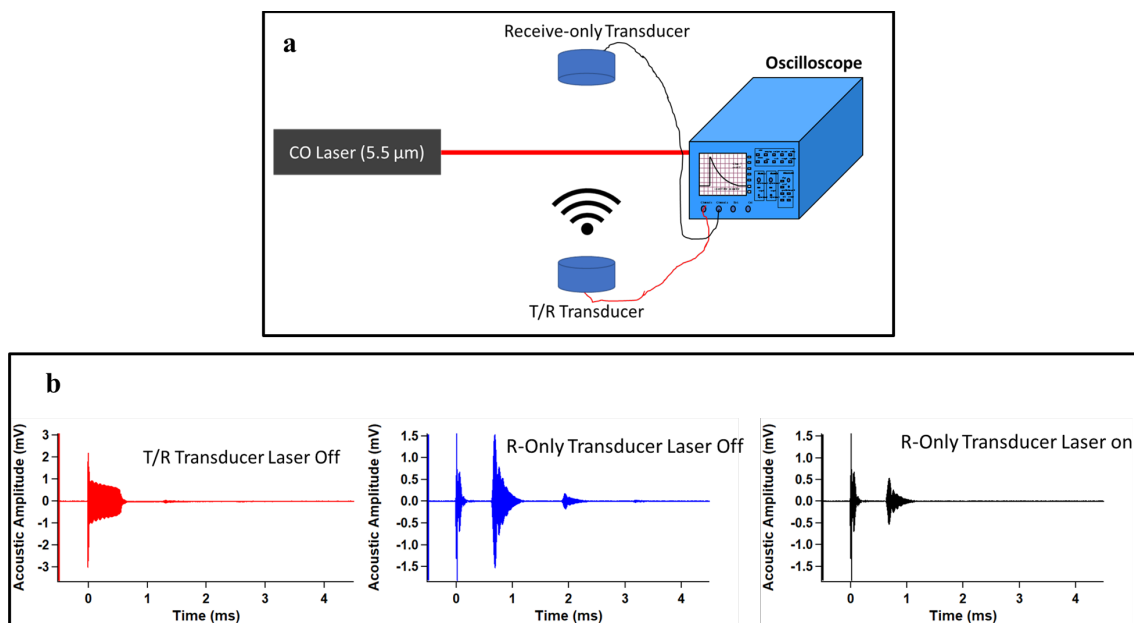


Figure 4: *a) Experimental setup for ultrasonic suppression efficiency measurements in ambient air. b) Ultrasonic transducer signals from ambient air suppression efficiency experiment. The three plots show the ultrasonic signal amplitudes of the initial output pulse by the transmit and receive (T/R) transducer (left), the received signal when the CO laser shutter is blocked (middle), and the received signal when the CO laser shutter was open (right.)*

The ultrasonic pulse amplitudes were monitored with and without the CO laser shutter open. No photoacoustic background subtraction was necessary for this experiment, as the photoacoustic background signals associated with the water vapor absorption of the CO laser is out of the detection range of the ultrasonic transducers. To synchronize the timing of the transducers and the laser, triggering was performed using the initial pulse of the ultrasonic transducer. The receiving transducer signal was then averaged over 100 acquisitions on the oscilloscope as previously to provide an average signal for suppression measurements.

As seen in Figure 4b, the ultrasonic transmission of the 150 kHz ultrasonic wave can be easily observed by the receiving microphone, after an initial output trigger pulse is generated by the Transmit/Receive (T/R) transducer. From the data, we can see that after the initial output pulse, the signal measured by the receiving transducer occurs approximately 0.8 ms later. The center graph in Figure 4b, shows the ultrasonic signal amplitude, when the CO laser shutter is closed (no THORS barrier present), with an amplitude of approximately 3 mV (peak-to-peak). Once the CO laser shutter is opened and the THORS barrier has formed in the path of the ultrasonic pulse (right most graph in Figure 4b), a marked decrease in ultrasonic signal amplitude (i.e., less than 1 mV) is observed. These results demonstrate not only the ability to efficiently manipulate acoustic waves via THORS in ambient environments, but also the ability to extend this acoustic manipulation to ultrasonic frequencies as well as the previously demonstrated audible range. Furthermore, the ultrasonic suppression efficiencies in these unoptimized THORS studies in ambient air, $59 \pm 8 \%$, are significantly greater than audible suppressions previously measured in an ethanol environment.

CONCLUSION

The ability to optically steer acoustic wave around physical barriers has been demonstrated using THORS, opening up the possibility of dynamically manipulating acoustic waves without physical acoustic barriers. Additionally, preliminary studies have shown that THORS barriers also work in ambient conditions, using atmospheric water vapor as the absorbing species and a 5.5 μm CO laser for excitation.

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