



A Novel Approach to Transmit Audio Content Over a Secure Communication Channel by Using Light Optics Under the Acousto-Optic Premise

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Abstract. This research paper discloses a novel method to transmit audio content over a secure communication channel by using light optics. The proposal uses Light-based Doppler Interferometry (LDI) to measure sound-field in the room. The measured sound-field values are used to create silence bubbles at the sender and recipient side by using hybrid active noise-cancellation to ensure effective communication. An audio signal is picked up from the speaker placed at the sender's side and is used to modulate the current source that drives a light emitting diode (LED). Upon audio-to-light conversion, the output optical signal is transmitted through the air to the intended recipient present at the other end of the room, who is some distance away from the sender. The experiments were performed using the LED light and a laser diode separately to explore different options available for indoor communication. According to the experimental results, LED light could transmit 12 dB more power than the laser diode across different audio frequencies for both setups of no air gap (i.e. 0 cm) and an air gap of 4 cm between the light source and photodetector. Also, it was identified that the laser diode transmitted consistent power for a known distance as compared to LED light. The attenuation for LED light and laser diode with respect to distance was found to be ≈ 5.5 dB/cm and ≈ 4.9 dB/cm respectively.

Keywords: LED Light · Audio Content Transmission · Light-based Doppler Interferometry (LDI) · Sound-Field Measurements · Hybrid Active Noise Cancellation · Photodetector

1 Introduction

In today's digital world, cyberattacks have been rising at an alarming rate. Malware attack, Man-in-the-middle (MitM) attack, Phishing attack, Denial-of-service attack, and so on are putting individuals and enterprises data at risk. Irrespective of the encryption layers added over the communication channel, no communication can be regarded as 100% safe in today's day and age.

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With the growing market for Internet-of-Things (IoT) devices, such cyberattacks are only expected to shoot up. According to a Jan 2022 report ‘Global Cybersecurity Outlook 2022’ by World Economic Forum, each successful cyberattack incident in 2021 cost an enterprise a whopping \$3.6 million. Moreover, COVID19 added fuel to fire as the cybercrimes only grew exponentially during this period with each organization reporting to have faced 270 cyberattacks. Also, in 2021 the ransomware attacks saw a steep rise of 151% [1].

Moreover, attacks like MitM facilitate eavesdropping, which is a common problem experienced by corporate professionals where confidential data is on the line. With eavesdropping, the attacker can intercept, delete, or modify data that travels between two or more devices. Eavesdropping, which is also known as sniffing or snooping, primarily occurs in an unsecured network environment. However, with increased sophistication of Machine Learning (ML) and Artificial Intelligence (AI) algorithms, even secured networks are open to such attacks [2].

Looking at the current trend of cybercrimes, it has become inevitable to develop innovative solutions that make the data in transit more secure and safe. Various end-to-end encryption methods are already being employed to safeguard data in motion. Companies like Apple use it for their iMessage and FaceTime services along with Microsoft that uses it for Skype services [3]. However, such encryption methods are only making eavesdropping difficult, but not impossible. Moreover, as all of today’s devices are internet enabled, hence ensuring the safety of personal and confidential data has become even more crucial.

Recently, researchers from MIT Lincoln Laboratory developed a method for sending audible messages directly to an individual’s ear from a distance by using lasers [4]. Although the implemented technology is said to be safe from eavesdropping, lasers can be dangerous. Delivering a laser directly to a human’s ear can cause injury to a person’s skin, damage skin tissues due to high temperature of lasers, lead to skin burns, and plenty other problems [5].

Another option to leverage safe communication is by using the high frequency RF (i.e. radio frequency) signal. However, as the RF signal is widely used across devices, one disadvantage here is that it is difficult to determine whether the RF signal is detected by an unknown party. Hence, there seems to be a long standing need to develop a secure communication system that is free from eavesdropping while two or more individuals communicate.

2 Theory

In this paper we present an implementation of using an optical signal to transmit audio content between two communicators sitting in a room, typically in an office setting. The deployment can be enabled via a uniquely designed IoT device similar to a simple Bluetooth device that has multiple modules embedded in it. However, the present research focuses on the development of an innovative approach for audio message communication using light which can be incorporated in any IoT device in future.

2.1 Sound-Field Measurements Using LDI

In step-I, Light-based Doppler Interferometry (LDI) is used for sound-field measurement [6]. It senses, captures, and analyzes the spatial properties of the sound-field in a room arising from sound sources like people having discussions or points like walls, windows, floors, equipment, and so on. Conventionally, laser driven equipment is used for such measurements (i.e. Laser Doppler Interferometry) [7]. However, we use LEDs that showcase higher brightness and have the ability to act like tiny lasers but are safe to use [8]. Thus, we use this measured sound data for further optical light modulation. The LDI setup is shown in Fig. 1 below.

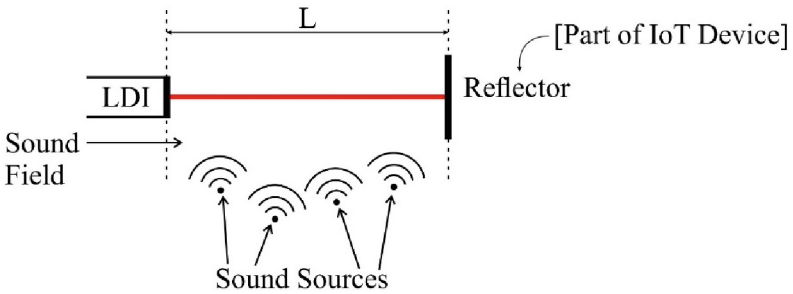


Fig. 1. Sound-field measurement setup

In our case, LDI is the part of the IoT device that transmits audio signals. Fundamentally, the LDI transmits focused light towards the intended user wearing a similar IoT device that has the reflector to reflect the light received from the sender. Thus, the reflected light is used to analyze the sound-field aspects. The light undergoes optical path change as it traverses the air gap between the sender and receiver due to the change in the refractive index occurring because of the surrounding sound-field or sound and light interaction.

For a transparent medium like air, the refractive index n varies with respect to density ρ which is given by equation $n = \rho K + 1$, where K is the Gladstone-Dale constant [9]. Now, with the presence of sound waves in the air medium, its density varies based on the acoustic pressure. This relation is given by the below equation:

$$\left(\frac{p + p_0}{p_0}\right) = \left(\frac{\rho}{\rho_0}\right)^\gamma$$

where, $p_0 =$ undisturbed pressure, $\rho_0 =$ density, and γ is the specific-heat ratio. Moreover, p and ρ_0 highlight the acoustic contribution to the overall pressure and density fields under static conditions.

This causes a change in the refractive index of the medium given by below equation:

$$n = n_0 + \frac{n_0 - 1}{\gamma p_0} p$$

where, n_0 = refractive index and the term $(n_0 - 1) / (\gamma p_0)$ represents the acousto-optic coefficient. Also, for sound-field measurement in air, the standard coefficient values are $\gamma = 1.40$ and $p_0 = 101325$ [10].

Let's consider a real life scenario of a corporate office room where sound-fields exist all around. In our approach, the light beam from LDI traverses the room by following a straight path L to the intended recipient. The LDI emits light in the direction of the receiver which gets scattered and is eventually reflected back to LDI by the reflector at the receiver's end as seen in the Fig. 1. As a result, the phase of the light beam ϕ emitted by LDI is determined based on its optical path. The phase is given by following equation:

$$\phi(L, t) = k_l \int_0^L n(r, t, l) dl$$

where $r \in \mathbb{R}^3$, t = time, k = wavelength of light, L = optical path. Moreover, the integral function here reveals that the detected optical phase is directly proportional to the sound-field pressure all along the light beam's optical path.

The phase evaluated in the above equation is basically sensed by the LDI. Thus, LDI's output is directly proportional to the phase change of the light beam which is given by below equation:

$$V(L, t) = \frac{1}{k_l n_0} \frac{d\phi}{dt},$$

Evaluating it all, the eventual vibration measured by the LDI is given by below equation:

$$V = U_w + \frac{n_0 - 1}{\gamma p_0 n_0} j\omega \int_0^L P(l) dl.$$

where, U_w = vibration of hard surfaces like walls, second term arises due to the acousto-optic effect. When the room where the users reside has hard walls and floors, then the term U_w can be neglected at mid and high frequencies. Thus the output signal V recorded by LDI is only the result of the acousto-optic effect [7, 10].

In summary, the above equation indicates that the measured signal V is proportional to the sound-field that's projected along the path of the light beam.

2.2 Hybrid Active Noise Cancellation

In step-II, the measured signal or vibrational values V are used for generating active noise cancellation signals at the communicating parties. In our case, we use hybrid active noise cancellation that combines both feedforward and feedback technology for generating noise-free silence bubbles around the device wearer's ear [11]. Feedforward typically cancels the ambient noise while the feedback monitors what the user hears and cancels the internal noise if any. This illustration is shown in Fig. 2.

The entire procedure basically creates a silence bubble around the communicating users which is similar to a virtual silence zone. The functionality benefits the users as the surrounding noise or sounds within the room are negated entirely to enable noise-free focused audio communication.

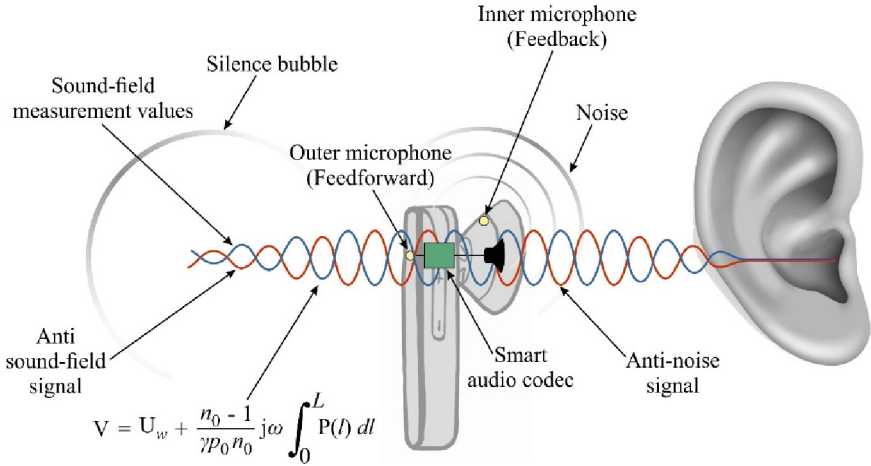


Fig. 2. Hybrid active noise cancellation

2.3 Modulate LED Power to Transmit Audio

In step-III, the sender speaks over the speaker to transmit the audio content. The speaker is connected to the light modulating unit that modulates the optical current source providing power to the LED. Note that the LED light used to transmit audio content is different from LEDs used in the LDI.

The modulated light is then allowed to propagate through the air gap between the sender and receiver. Upon being emitted, it is received by the photodetector at the recipient's end. This photodetector is further connected to the output speaker to produce the audio content sent by the sender.

3 Experimental Design

In our experiments, the audio messages to be transmitted do not exceed 5Vpp. The current source for the LED / laser diode is of 10V, thereby making the audio range permissible. Also, the input current to the current source does not exceed the limit of 5 mA/V. As the current source is in the low bandwidth mode, the input it takes is around 14–15 kHz. Since the input frequency range for music lies between 20 Hz to 10 kHz, 14–15 kHz is acceptable. Moreover, the gain of the photodetector should not exceed a limit as the output signal should not go beyond 5Vpp. Also, at 2 cm from the speaker, we placed a smartphone decibel meter that uses a sound level meter app (Decibel X) to measure the audio level of the received signal.

We have used a 5 mm green LED as light source and two 8 Ω 0.5W speakers for our experiments. The experimental layout is disclosed in Fig. 3 below:

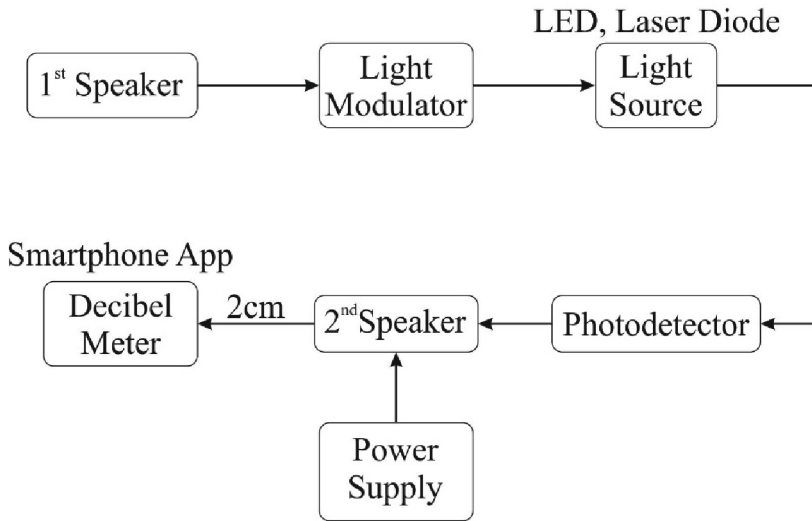


Fig. 3. Experimental layout

The portable testbed for LED light that validates the propositions of our research is represented in the below image. A similar setup was used with a laser diode which is not shown here. Also, please note that the power supply unit used to supply power to the circuit and voltage meter used to measure voltages at different points in the circuit is not shown in the captured image (Fig. 4):

To determine the results, the testbed shown in Fig. 4 was used where we supplied music as an input audio signal to the first speaker (8 Ω 0.5 W). The music was chosen in a manner which ensured that the notes within the song were made up of multiple frequencies. We also used an indigenously made light modulating unit that controlled the power to the LED/laser diode. The photodetector we used for experimental purposes is a light sensor that is placed at 0 cm and 4 cm from the LED/laser diode in the initial and final settings respectively. Moreover, the light sensor is further connected to the second speaker that reproduces the original audio signal. The smartphone sound meter is placed at a distance of 2 cm from the second speaker (8 Ω 0.5 W). The sound meter not only records the sound decibels but also shows the fluctuations in the output frequencies of the received audio signal.

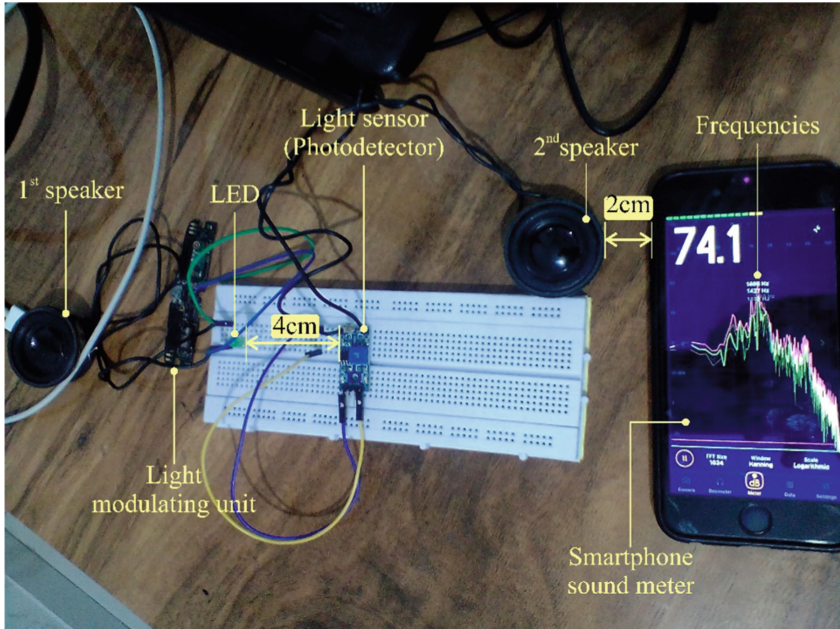


Fig. 4. Testbed for audio transmission using LED placed at 4 cm from the photodetector

4 Testing

To test the experimental setup, the voltage output at each signal processing juncture was measured. Moreover, to ensure that the voltage fluctuations were consistent for all measurements, the data was measured while the music was being played at the first speaker. It was identified that the voltage measured at the output of the first speaker did not exceed 2 Vpp. Also, the voltage of the photodetector placed on the opposite side of the LED light/laser diode with gain on turned out to be less than 1Vpp. Also, the output of the second speaker connected to the power supply was about 2.5 Vpp. All the measured voltages showcased an acceptable range.

In the initial iteration, the experimental setup did not produce the audible sound as required. When music with high frequency notes was played, the speakers produced a crashing noise. When verified, it was found that the LED had a current source that was set to 45 mA. In the following iteration, when the current source was reduced to 35 mA, music was clearly heard.

5 Results

As stated earlier, we used the LED and laser diode separately as optical sources and measured decibel readings for different settings. Initially, the audio content transmission for zero air gap between LED and photodetector was measured, followed by audio transmission with the air gap of 4cm. Moreover, we used a free, open source audio software

named Audacity to record and measure attenuation of different sound frequencies sent through the developed system [12]. All the results evaluated using the testbed shown in Fig. 4 are outlined in the below tables.

Use case-I: No gap between the LED/laser diode and the photodetector. The decibel reading for this use case are as follows:

Table 1. Decibel Readings for No Air Gap Configuration

Sr. No	f(Hz)	LED (dB)	Laser diode (dB)
1	80	91	79
2	500	109	100
3	1000	108	98
4	2500	103	92
5	5000	104	95

According to Table 1, for all measured frequencies, LED light is able to transmit sound with more decibel level as compared to laser diode. The attenuation for each light source with zero air gap is tabulated below:

Table 2. Attenuation for LED and Laser Diode with No Air Gap

Sr. No	f(Hz)	LED loss (dB)	Laser diode loss (dB)
1	80	-3	7
2	500	2	9
3	1000	0	7
4	2500	-5	3
5	5000	-11	-3

According to Table 2, the laser diode shows a gain of 7 to 9 dB on average for all measured frequencies in a no air gap setup as compared to LED.

Use case-II: Upon testing the no air gap scenario, we increased the distance between the LED/laser diode and the photodetector to 4 cm and recorded the decibel reading and corresponding attenuation. The readings are given in the Tables 3 and 4:

Table 3. Decibel Reading for Air Gap of 4cm

Sr. No	f(Hz)	LED (dB)	Laser diode (dB)
1	80	69	66
2	500	94	83
3	1000	95	82
4	2500	87	76
5	5000	89	77

Further, the attenuation for LED and laser diode was determined with an air gap of 4 cm. The readings are as given below:

Table 4. Attenuation for LED and Laser Diode with 4cm Air Gap

Sr. No	f(Hz)	LED loss (dB)	Laser diode loss (dB)
1	80	17	20
2	500	17	26
3	1000	15	24
4	2500	11	19
5	5000	6	15

On observing the two configurations, it was identified that the average attenuation for LED and laser diode with respect to distance was ≈ 5.5 dB/cm and ≈ 4.9 dB/cm respectively.

It is worth noting that we have successfully implemented optical light-based audio data transmission as desired. Since the developed prototype uses LED light instead of harmful lasers, it seems to have an edge over the laser-based audio message transmission method designed by MIT Lincoln Laboratory researchers in 2019 [4, 5]. We are currently working on the practical implementation of the remaining two modules of ‘LDI based sound-field measurements’ and ‘hybrid active noise cancellation.’ Upon realization, we will integrate these modules with the already developed light-based audio transmission module.

6 Advantages and Applications

Today, one can say that any kind of wireless communication is inevitably vulnerable to external attacks. Our research tries to isolate one such communication that does not involve the usage of the internet or any other external network. The communication

method is restricted to living rooms in households, corporate office rooms, and auditoriums where the enclosed space is without any obstacles or partitions such as glass partition, wooden partition, and so on. Implying, the open room space allows barrier-free passage of optical light. With such room configuration and novel communication method the chances of eavesdropping and other cyberattacks are potentially brought down to zero. Thereby, establishing a unique communication channel for user interaction.

Corporate professionals can use the technology for meetings, conferences, or group discussions while physically staying in the same office space. For example, let's say a manager in an IT firm wishes to have a physical meeting with two of his subordinates. In a general scenario, the manager has to either call the individuals at his desk or take them to a conference room where other company employees are not present while they discuss project related matters.

However, with the proposed technology, the manager can do it seamlessly by sitting at his own desk. In this case, let's assume that all the intended users are wearing the IoT device that enables light-based audio communication. Initially the manager identifies the employees with whom he wants to have a collaborative discussion. Once identified, the target employees are notified about it on their respective IoT devices. Upon notifying, the manager's IoT device then performs sound-field measurement of that very room. Once that's done, the sound-field measurement values are communicated to the participating user devices. Then, the devices used by all three users' initiate noise cancellation to create silence zones for each of them based on the sound-field values. These virtual silence bubbles that are noise-free then allow communication between participating users. Thus, a group meeting of three is conducted in the same office arena without having the users move to another isolated conference room or space.

Figure 5 is a representation of the proposed light-based audio transmission approach in an office setting by establishing a secure communication channel between the communicating users.

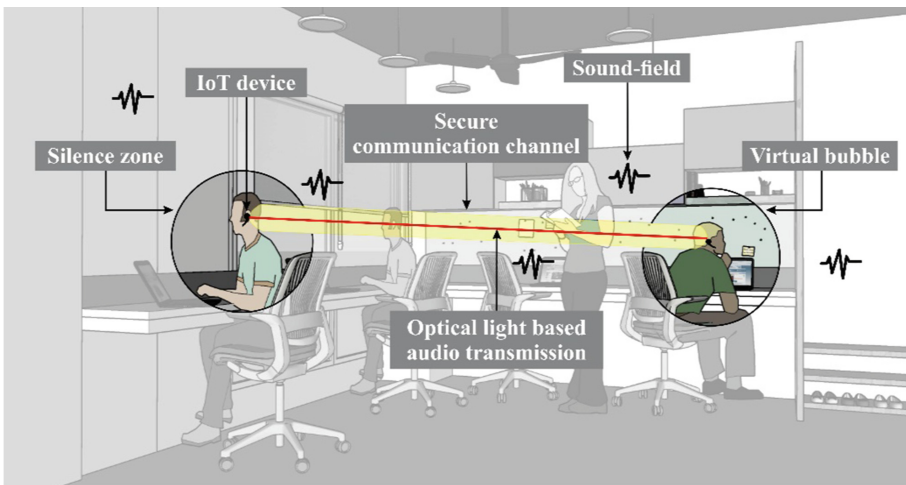


Fig. 5. Light-based audio transmission in an office setting

7 Conclusion

This research proposes a unique approach for sending audio content to intended users in a room by harnessing the properties of light. The method employs a three step process for audio transmission: sound-field measurement using LDI, hybrid active noise cancellation, and audio files transmission by manipulating LED power. Moreover, sound-field parameters enable noise cancellation phenomena, thereby highlighting a novel process for creating silence zones at the sender and receiver end while communicating.

On the experimental front, our research revealed that one can use LED light instead of lasers for audio content transmission. It is a safer approach for point-to-point communication. The results revealed that LED light could transmit 12 dB more power than the laser diode across different audio frequencies for configurations of 0cm and 4cm air gap between the light source and photodetector. Lasers had lower attenuation of ≈ 4.9 dB/cm over distance as compared to LED light attenuation of ≈ 5.5 dB/cm. Since lasers use polarized light, they use less power for transmission as compared to LED light, thereby justifying the attenuation values. However, in a room setting, since the distance is not much of a concern, LED light beams can be a go-to choice for delivering audio messages from one corner of the room to another.

8 Future Work

In future, we intend to use a lens (e.g. bi-convex lens) between the audio transmitter and receiver to increase the intensity of light at the photodetector. Such an arrangement would inevitably increase the power received at the photodetector, thereby lowering the loss for used light sources.

Secondly, we also intend to use an amplifier (e.g. a non-inverting amplifier) between the speaker and photodetector. This is because, without the amplifier, although the music is distinguishable, there is an element of noise that still persists in the audio signals produced by the second speaker. Thus, by adding the amplifier, we would be adding gain to the speakers which would reduce the 'noise variable' from the speaker that reproduces audio signal at the receiver end. This would make the audio messages more clear to the intended user.

We also intend to work on adding security layers to the developed model to ensure that it is resistant to any form of external penetration or attack. Moreover, we intend to test the developed prototype under different lighting conditions. This will give us key insights into whether our model can withstand interference from external lights whilst still maintaining a secure communication.

Acknowledgement. I would like to extend my sincere gratitude to Dr. A. S. Kanade for his relentless support during my research work.

Conflict of Interest. The authors declare that they have no conflict of interest.

References

1. World Economic Forum, Global Cybersecurity Outlook 2022, 18 January 2022
2. Miao, Y., Chen, C., Pan, L., Han, Q.-L., Zhang, J., Xiang, Y.: Machine learning based cyber attacks targeting on controlled information: a survey, *ACM Comput. Surv.* **54**(7), Article No. 139, 1–36 (2022). <https://doi.org/10.1145/3465171>, 18 July 2021
3. Greenemeier, L.: Fact or Fiction: encryption prevents digital eavesdropping, *Scientific American*, 15 July (2013)
4. Foy, K.: A laser can deliver messages directly to your ear from across the room, *Communications & Community Outreach Office, Lincoln Laboratory, Massachusetts Institute of Technology*, 4 November (2019)
5. Laser Hazards-General, Environmental Health and Safety, Oregon State University
6. Olsson, E.: Doctoral thesis on sound source localization from laser vibrometry recordings. Luleå University of Technology, Department of Applied Physics and Mechanical Engineering, Division of Experimental Mechanics **23**ISSN: 1402–1544 (2007)
7. Fernandez-Grande, E., Verburg, S., Hahmann, M.: Acousto-optic capture of the sound field in a room based on sparse measurement data. In: *Proceedings of the International Symposium on Room Acoustics, Amsterdam, Netherlands, 15 to 17 September (2019)*
8. National Institute of Standards and Technology (NIST). A light bright and tiny: Scientists build a better nanoscale LED: New design overcomes long-standing LED efficiency problem -- and can transform into a laser to boot. *ScienceDaily*. ScienceDaily, 14 August (2020)
9. Tatar, K.: Doctoral Thesis on Machine tool vibrations and violin sound fields studied using laser vibrometry. Luleå University of Technology, Department of Applied Physics and Mechanical Engineering, Division of Experimental Mechanics **27**ISSN: 1402-1757 (2006)
10. Ishikawa, K., Shiraki, Y., Moriya, T., et al.: Low-noise optical measurement of sound using midfringe locked interferometer with differential detection. *Acoustical Soc. Am., J. Acoustical Soc. Am.* **150**(1514), 1523 (2021). <https://doi.org/10.1121/10.0005939>
11. Triggs, R.: SoundGuys, Active noise cancelling (ANC) technology types explained, 29 October (2021)
12. Audacity (2022). <https://www.audacityteam.org/download/>