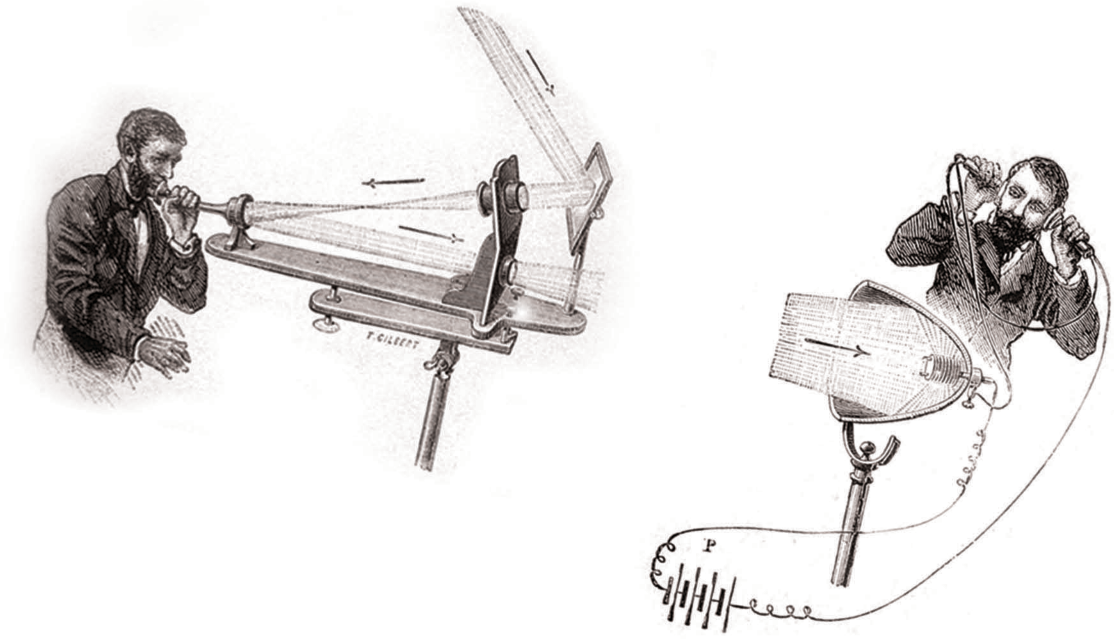
BACHELOR ASSIGNMENT APPLIED PHYSICS

THE PHOTOPHONE

Historical research revived with 21st century technology



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ABSTRACT

This report is the result of a research assignment, part of the bachelor study Applied Physics. The project is done at the Biomedical Photonic Imaging Group (BMPI) of the University of Twente.

The main goal of the project is to create a device to demonstrate the photoacoustic effect. This setup is based on the Photophone, invented by Professor Alexander Graham Bell in 1880. The device has to transmit an audio signal (speech) by modulating light intensity and convert the signal back to audio waves making use of the photoacoustic effect. The final design has to have a robust and simple construction so it can be used for educational purposes. To keep as close as possible to the original design by Bell, the target is to design both modulator as receiver without electronics.

The research is split in two parts. First, to convert modulated light into sound, research is done on absorber material influence, light intensity response, absorption cell dimensions influence and frequency response. Second, to modulate light with audio waves with a mechanical setup, research is done on different modulations techniques, frequency responses and modulation depths. From research on the absorption cell can be concluded that the modulated light beam has to have an AC signal of at least 50 mW to be audible without electronic amplification. From research on modulation techniques can be concluded that it is difficult to create a modulation of larger than 5 mW AC signal, due to optical safety requirements and modulation technique limits.

The research concludes that the modulated light signal is too weak to make the photoacoustic effect audible. Instead, for the construction of the final demonstration setup, electronic light modulation is used. A 5 Watt LED (with optical power of approx. 250 mW) is directly modulated by an electronic audio signal with a small amplifier. The receiver is slightly optimized on basis of the results from the research. The demonstration setup produces a clearly audible sound.

FOREWORD

This research project is the final assignment of my bachelor Applied Physics at the University of Twente. I had the honor to proceed in the photoacoustic pioneers work performed by Professor Alexander Graham Bell around 1880. The assignment made me realize how ingenious his work was, taking into account that all measurements were performed without electronic measurement equipment. Despite of the knowledge acquired in 130 year of research, most of his report is still usable and correct. It clearly shows the importance of thoroughly performed fundamental research.

The assignment challenged me to apply a very wide selection of the lectures and lab exercises I followed during my bachelor study. During the research I realized that this acquired knowledge and skills are a toolbox you need to get familiar with. In real scientific research no direct answers can be found in textbooks or literature, instead they are found in the combination with your own knowledge and skills. After a difficult and slow research process, I finally combined all resources required to solve the puzzle and see the big picture. The result reminds me on a statement made by fellow students; once the puzzle is solved, the result often seems quite obvious. However, for me this only confirms that I successfully proceeded in a piece of personal academic development.

I would like to thank my daily supervisor Steffen for the advice in the research process and the comments on all the numerous versions of my report. Also I would like to thank the technical staff, Johan and Erwin, for the assistance in the lab and help in building the final demonstration model. Furthermore I would like the entire BMPI group, for the advice during work meetings and when walking by in the lab. Although I should perform this research on my own, I would not be able to finish the project without all your help.

Jasper Hoving
June 2012

TABLE OF CONTENTS

1. INTRODUCTION

The photophone is a research project of Professor Bell and was performed around 1880. The discoveries made more than a century ago, still have a large influence on today's developments in modern research. However, most discoveries made by Professor Bell were accidentally found as a side product of his main research: The build of an optical telephone. This project tries to finish this build, with use of modern techniques and knowledge. This chapter will introduce some history, the current use of photoacoustic techniques at the BMPI group and the assignment.

1.1 HISTORY

The photophone was invented in 1880 by Professor Alexander Graham Bell. He discovered that certain materials produce an audible sound when they are exposed to a rapidly interrupted sunbeam. He also discovered that the frequency of the beam interruption had a straight correlation with the frequency of the produced tone. With this research he discovered (without knowing) the photoacoustic effect. When a light beam heats a light absorbing material, the material and surrounding air expands and sends out a pressure wave. When the light beam is interrupted on a certain frequency, the material will send out pressure waves with the same frequency.

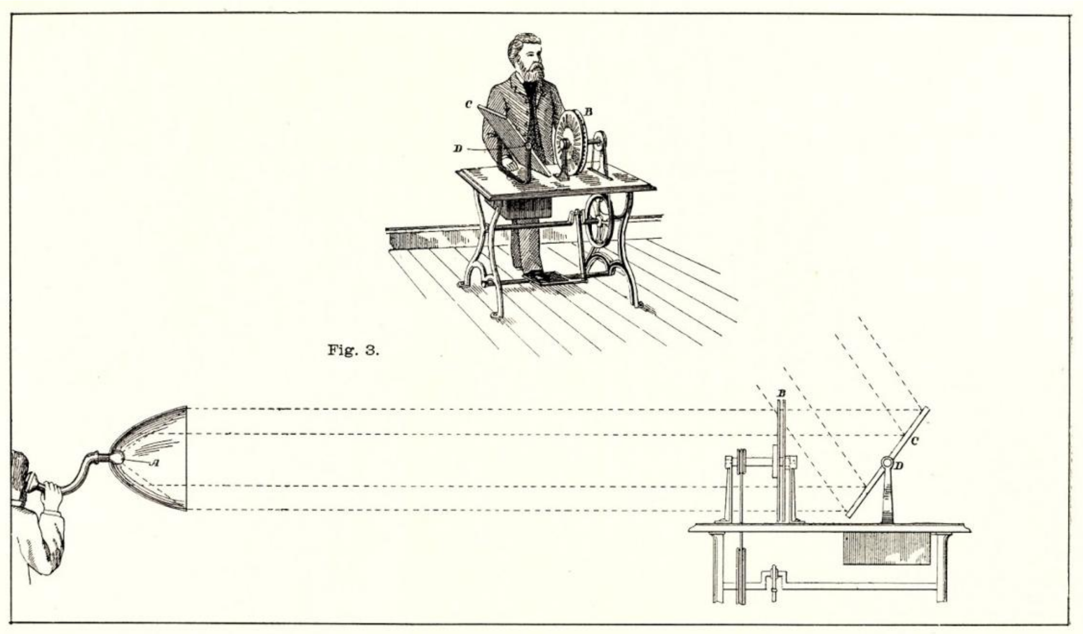


Figure 1 – Bell's optical chopper setup

For the modulation of the sunbeam Bell used a construction of two similar slotted wheels as shown in figure 1. The first one is set at a fixed position and the second one is rotating at a constant angular velocity. With this construction the intensity of the sunbeam is modulated at a frequency depending on the angular velocity and the number of slots in the wheel. For the receiving of the signal, he used a parabolic mirror with a small glass tube in the focal point. This tube was filled with different absorber materials. A lot of research was performed on which absorber material achieves the highest sound level.

During his research Bell also discovered a totally different effect, which made him abandon his research on the photoacoustic effect. When the material selenium was irradiated with an alternating light intensity its resistivity changed proportional to the intensity. By wiring a telephone horn and a battery to this material, he created an electronic version of the photoacoustic effect. This version had a much higher sensitivity, because it could easily be amplified by applying a higher voltage.

With this new and improved receiver, it was possible to transfer speech by light. To do this a flexible mirror membrane was placed in front of an acoustic horn. A lens was used to focus the parallel sunlight beam just before the mirror, as shown in figure 2. A second lens was used to make the outgoing beam parallel again. When sound waves hit the mirror, this mirror bends a fraction and the optical path length between the lenses shortens or extends. When the optical path length shortens, the outgoing beam diverges more and will have a lower intensity at the receiver. These small variations in intensity can be converted into an electrical signal by the selenium.

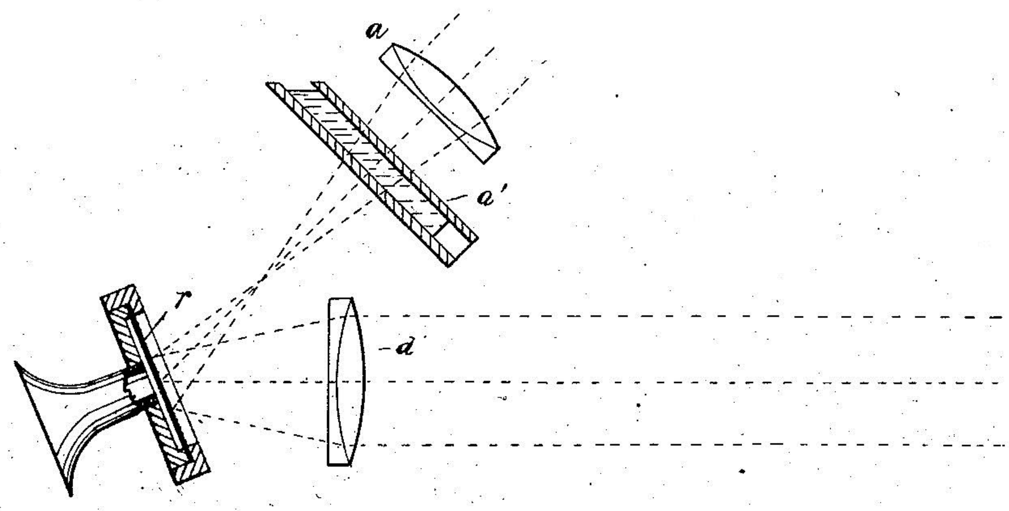


Figure 2 - The vibrating mirror setup

With this setup Bell managed to send speech from a roof to his laboratory over a distance of 213 meters. A larger distance was very difficult, because the rotation of the earth changes the direction of the incoming sunbeam and creates the need to continuously realign the setup.

A practical problem in the use of this setup was the need of direct sunlight. A few decades later electricity and powerful electrical light sources could replace this need and a large number of applications were developed.

- In 1927 it was used to add soundtracks to a movie in a system called the RCA Photophone[1]. Next to film pictures a line was printed with an alternating darkness corresponding to the sound waves. When a light beam was projected through this line, the intensity is modulated and a receiver at the other side of the film could reproduce the audio signal.
- From 1939 until 1950 it was used as a communication device for the navy. With high power (>1000 watt) tungsten light bulbs the German and American marine managed to communicate over a distance of more than 10 kilometers.
- Around 1970, when LEDs, laser diodes and fiber optics were invented, the principle of the photophone was used for fiber optic communication.
- In 1977 the first infra-red remote control was invented. Despite the application is totally different from the photophone, the construction is still the same. A remote control sends out intensity modulated IR light and a photoresistor (or photodiode) converts the signal back.

Today there are much more applications but they all use the old principle of the photophone. A signal is used to modulate light intensity and a photoresistor or photodiode is used to convert it back. Bell always believed that the photophone was his most important invention, but probably couldn't imagine the applications and spin-offs technologies used nowadays.

[1] http://en.wikipedia.org/wiki/RCA_Photophone

1.2 PHOTOACOUSTICS

Bell discovered that the selenium based receiver was much more useful for communication devices than the photoacoustic receiver. However, this research focuses on the photoacoustic effect and continues where Bell (and all other applications in the following century) made the switch to electric receiver.

The photoacoustic effect is nowadays used in many research projects. At BMPI, the group where this research was done, the effect is used to measure structures in biological tissue. This paragraph will introduce the physics behind the photoacoustic effect and give a short introduction of the application at BMPI.

1.2.1 PHYSICS

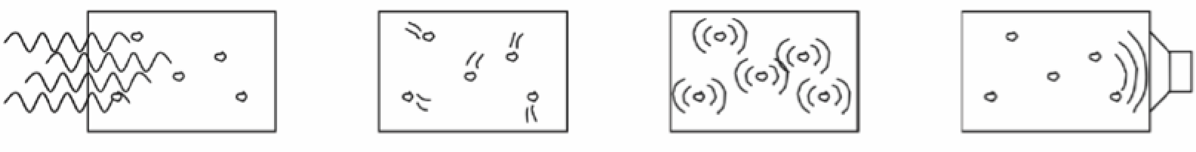
The photoacoustic effect is based on two events. The first event is the optical absorption of the energy from the light beam that results in heating of the sample. The produced temperature difference with the surroundings depends on the optical absorption and the heat capacity of the sample. A high absorption and a low heat capacity obviously result in the highest temperature difference.

The modulated light always has a DC and an AC component. The DC part will establish an equilibrium temperature, depending on the thermal conductivity of the sample and its surroundings. The AC component will create a small variation on this temperature, which eventually will create the signal. The photoacoustic signal is totally independent of the DC component, even though the AC component is a fraction of the DC signal.

The second event is the conversion of temperature differences into pressure waves. There are two different phenomena that result in pressure waves; thermal waves and acoustic waves.

- ***(Photo)thermal waves*** are created by the expansion of the gas surrounding the sample. When there is a temperature difference between the gas and the sample, the heat is transferred to the gas which expands due to the increasing temperature. This expansion creates a pressure wave (as sketched in figure 3).
- ***(Photo)acoustic waves*** are created by the expansion and contraction of the sample material itself. When the temperature of the sample is changing, it will expand proportional to the thermal expansion coefficient. Materials with a low heat capacity and a high thermal expansion coefficient will give strong acoustic waves.

In this research all absorbing materials will be surrounded by air, so strictly spoken this research will demonstrate photothermal waves and not the photoacoustic waves used at BMPI.



(a) (b) (c) (d)

Figure 3 - (a) Absorption, (b) Heat exchange, (c) Expansion, (d) Wave front

1.2.2 PHOTO ACOUSTICS AT BMPI

At the BMPI group one of the main projects is research on imaging techniques using the photoacoustic effect. A very short (typically a few ns) and intense laser pulse is sent into a piece of biological tissue. This light pulse triggers the photoacoustic effect and creates acoustic waves. The produced waves have a very wide frequency spectrum (in the range of MHz), containing information about the absorbing material. Ultrasound transducers record these waves and computer software reconstructs a visual image of the tissue. In this reconstruction process speed of sound corrections are involved in order to get a spatial distribution of optical absorbers from which the waves are emitted.

When comparing this technique with the photophone, the photoacoustic imaging concept is a kind of high-tech photophone. By sending light at a material and listening to the response waves one can say something about the material. Around 1900 the only measurable result was the difference between a louder or weaker sound, from which some conclusions about for instance the optical absorbance (i.e. the color) could be drawn. This was a revolutionary step, because one could say something about a material without seeing or touching it, but by listening to the sound. After more than a century of research and technological developments, we still use the same technique of sending light and listening to the produced sound. The main improvement is the replacement of the human ear by ultrasonic transducers and advanced computer software. The work of BMPI and other groups enabled us to see with our (high-tech) 'ears'.

1.3 THE ASSIGNMENT

Because the technology used in photoacoustic imaging is difficult to explain, the original photophone is a perfect device for demonstration purposes. By listening the sound waves produced by light, non-technical people can easily understand the principle of photoacoustics. The purpose of this project is doing research on the photophone and using the results to build one.

This research project has two main reference projects. The first one is the original research report from Bell [1] and the second one is a series of articles written by Kleinman et al. [2],[3],[4]. The Bell project did never achieve to make speech audible with the photoacoustic effect. It only managed to transmit low frequencies. A goal of this research will be to find out the limitations of the original setup that prevented the device from functioning. The research of Kleinman et al. is done between 1970 and 1980. Their goal was to create an optical telephone receiver, using glass fiber instead of electrical wire. They achieved to make a modulated light signal clearly audible on a usable sound level. This was done with a microscopic scale absorption cell (1 cubic mm), glass fibers, specialized acoustic transformers and electronic light modulation.

This project will try to achieve a compromise between the two projects; the simplicity and clarity of the project of Bell combined with the high tech solution of the Kleinman project. Where possible, electronics and exotic components are avoided to stay close to the original design and make the functioning principles of the device easy understandable.

Because there are a lot of different small research topics, this report will not be written in the usual structure of one general theoretic analysis, experimental results, discussion and conclusion. Chapter two contains research on the receiver cell and chapter three the modulation of the light beam. Because these are two totally different research topics, for clarity these chapters will be written independently. Both chapters conclude with a discussion of results, which will be used to design the demonstration device. Chapter four explains the construction of the device and applies the discussion results of the preceding chapters.

2. THE PHOTOACOUSTIC RECEIVER

This chapter describes the research on the receiver part of the photophone. There are several parameters and physical phenomena involved in converting modulated light into audio waves. The chapter will start with a simple setup based on the original photophone and use its results to select the research topics. Then all theoretic aspects from literature will be explained and experimental results will be presented. The chapter will finish with a discussion on the use of the results in the final design.

2.1 RESEARCH INTRODUCTION

A good starting point for this research seems to be the point where professor Bell stopped using the photoacoustic effect and started to use the selenium receiver. At this point he stated that a glass tube with a layer of 'lamp black' was the best absorber he could find to create audible waves. In the article "Hearing light" [5] a very simple experiment is described that is similar to the experiment done by Bell. One half of an ordinary glass jar is coated on the inside with a layer of soot from a burning candle as shown in figure 4. In the lid a small hole is made. Instead of modulating sunlight with slotted wheels, an ordinary 230 Volt light bulb is used. Because it is powered by a 50 Hz AC power source, the polarity will change 100 times per second. This will result in a modulation of the light output of 100 Hz. When the jar is hold close to a light bulb, a 100 Hz hum is clearly audible through the hole due to this intensity variation.

Figure 4 - Making an AC signal audible

From this basic setup four main questions arise which will form the main structure of this research part:

1. What is the influence of a different absorber material?
2. What is the influence of a different volume or shape of the absorber cell?
3. What is the influence of the light intensity?
4. What is the frequency response of the absorber material?

Theoretical analysis will be done and experimental research will be performed to illustrate the theoretic analysis.

2.2 THEORETIC ANALYSIS

2.2.1 ABSORBER MATERIAL PROPERTIES

As mentioned in the introduction, the absorber converts the energy of the light beam into heat and transfers it to the surrounding gas which expands. In the reports of Bell a rather extensive collection of measurements on liquids, gases and solids can be found. The best results were achieved with solids, so liquids and gases are kept out of the research.

Bell formulated in his report two conditions to get the highest sensitivity:

The loudest sounds are produced from substances in a loose, porous, spongy condition and from those that have the darkest or most absorbent colors.

From the Kleinman articles a more detailed description of ideal absorber material can be derived, but technically it states the same requirements as Bell did. To get a high sensitivity, a material has to have:

1. A dark color, so it converts most of the absorbed light into heat
2. A rough structure, so it hardly reflects light
3. A porous structure, so there is a lot of surface to ensure a good heat transfer to the gas
4. A low heat capacity and low thermal conductivity (thermodynamic properties), so the absorber heats quickly and transfers more heat to the gas

The best absorber material according to Bell is lampblack (soot) and according to Kleinman charred cotton fiber. Both materials consist mainly of carbon and match the four requirements stated above. Lampblack is created by holding the flame of a candle against the inside of a glass jar. Charred cotton is created by heating cotton to around 500 degrees Celsius for 15 minutes in a container without oxygen supply. Cotton is made of cellulose which consists of carbon, hydrogen and oxygen. The heating will release the oxygen and hydrogen (this process is called gasification) and a structure of carbon particles will remain.

2.2.2 ABSORBER CELL DIMENSIONS

To determine an optimal size for the absorption cell, three effects should be considered.

1. The volume of the cell has its influence on the produced sound pressure and acoustical impedance
2. The frequency of resonances depends on the dimensions of the cell
3. The dimensions of the cell have to be large enough to clearly see the material been illuminated and to ensure easy optical alignment

For this research two boundary conditions are assumed. First, only the frequency range from 200 to 2000 Hz is relevant because this is the range of speech. Second, problems with acoustical impedance mismatches are avoided because optimizing acoustical transformers is somewhat beyond the scope of this research. The focus is on the photoacoustic effect.

2.2.2.1 CELL VOLUME

For the influence of the absorption cell volume, reports of Bell and Kleinman are compared. Bell used a relative large (in the order of 10 ml) glass tube as absorption cell, illuminated by 2000 mW of solar light. Kleinman used a very small (0.001 ml) metal cell, directly illuminated by a small glass fiber and an optical power of 3 mW. This large increase of sensitivity is mainly accomplished by using a smaller volume. For small volumes of gas (assuming equal pressure distribution over the volume) Kleinman states [2] the pressure increase is inversely proportional to the volume, as stated in equation (1).

$$\frac{dp}{dt} = \frac{\gamma p_0 s}{V} \qquad (1)$$

In this equation γ is the specific heat ratio (C_P/C_V), p_0 is atmospheric pressure and s is the volume flow due to the expansion of the heated gas. The volume flow s is only dependent on the optical power input, as shown further in paragraph 2.2.4.

When very small volumes are used, the pressure differences will become very high and this will result in acoustic impedance (the ratio between pressure and particle velocity) mismatch. This means that a lot of energy is used to create the pressure differences, but almost no particle movement is generated. This can be corrected with the use of an acoustic transformer (a horn), but (as mentioned) that is beyond the scope of the research. To avoid this problem, the used cell should have the same diameter as the measurement microphone. In an air-tight setup the microphone will measure pressure differences (in time) directly without acoustical impedance issues.

2.2.2.2 Resonance frequencies

The most common shape of a glass container in a lab is a cylindrical tube. When using a cylindrical tube with stiff reflecting walls, standing waves can be created. According to an article of Benjamin T. Spike [6], in an ideal situation the acoustic signal can be amplified a 1000 times at the resonance frequency. In a spherical container this can be even up to a factor of 10000. This can be very useful for high precision measurements, for instance of pollution in air, but is not wanted when designing an audio receiver with a flat frequency response.

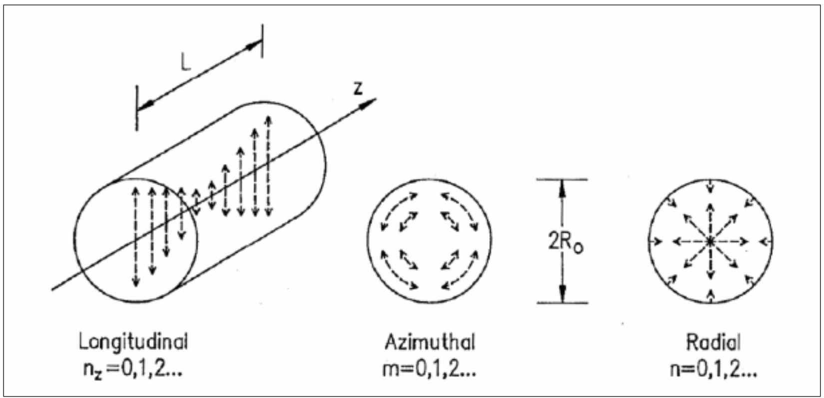


Figure 5 - Different resonant modes

In figure 5 the different resonant modes in a cylindrical tube are shown. It is possible to calculate the complete range of resonant frequencies for each direction but the purpose of the calculation is only to make sure resonant frequencies are not interfering with the measurement results.

To calculate the lowest frequency the longest resonance length is taken, which can be the length or perimeter of the cylinder. For a cylindrical cell with a length of 3 cm and a diameter of 1 cm, the main resonant frequency is around 11 kHz. The first sub-harmonic will be at 5.5 kHz and because it is a closed system lower sub-harmonics will not occur.

Because the goal of the setup is the transmission of speech, which has a frequency range of around 200 to 2000 Hz, this resonance frequency will not influence the measurements. Smaller cells will have higher resonant frequencies, so no measurement influence is expected.

2.2.2.3 Optimal size for demonstration setup

For the use in a demonstration setup, the cell has to be large enough to easily focus the light on the absorber material with a hand-held parabolic mirror device. This means the cell has to be long and thick enough to catch the light if the incoming beam is off-axis.

Summarizing; from a practical point of view a larger cell is better, but to create high pressures a smaller cell is better. The diameter of the cell should always be similar or larger than the microphone diameter to avoid acoustic impedance problems. The length should be long enough to easily catch the light.

2.2.3 LIGHT INTENSITY

From physical intuition, light intensity is expected to have a fairly linear effect on the sound wave pressure. When the light intensity is doubled, the temperature difference is doubled as well as the pressure wave amplitude. However, the heating of the absorber material is not a perfect adiabatic process and at higher temperatures more heat is lost.

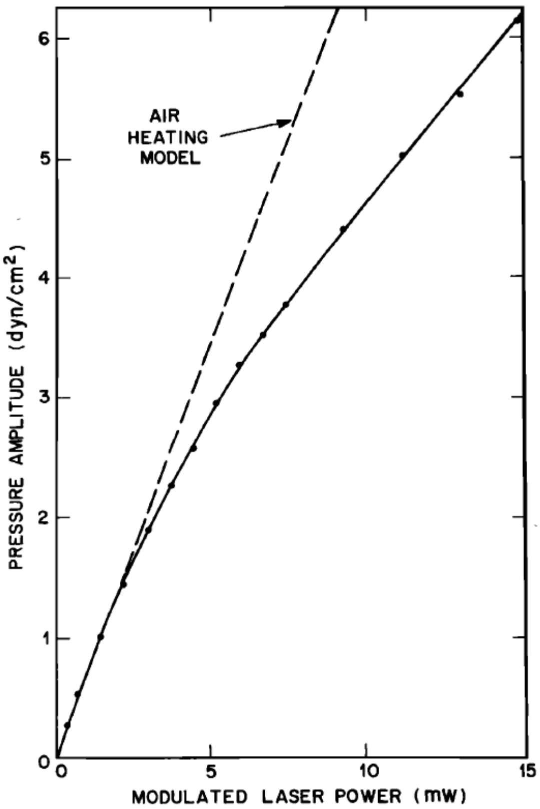


Figure 6 – Light intensity response [2]

Kleinman compares the model of “light absorbing air[2]” with the measurements of his setup on a fixed frequency in figure 6. He states that for low intensities, the temperature of the gas is strongly coupled to the temperature of the absorber material and shows a linear response. For higher intensities the coupling is less strong and pressure amplitudes deviate largely from the air heating model. A physical explanation is not given; he states that the charred cotton is “an incompletely understood component in the system”.

[2] Imaginary black air, the air is directly heated without the intermediate step of the absorber material

2.2.4 FREQUENCY RESPONSE

The production of sound on different frequencies is extensively described by Kleinman. The whole theoretic background is too large to explain in this report, but for general understanding two general equations (2 and 3) are sufficient. They describe the sound pressure in the frequency domain.

$$p = \frac{i\gamma p_0 s(\omega)}{\omega V} \tag{2}$$

$$s(\omega) = [(\gamma_0 - 1)/\gamma_0 p_0]\; G_A G_M G_\omega P_\omega \tag{3}$$

In these equations;

$s(\omega)$	=	Particle speed of the sound source
γ, γ_0	=	Material/atmospheric specific heat ratio (constants)
p, p_0	=	Sound/Atmospheric pressure
V	=	Volume of absorber cell
G_A	=	The utilization factor for the light input
G_M	=	A thermodynamic constant of the absorbing medium
G_ω	=	The thermal dissipation function, frequency dependent
P_ω	=	The optical power function, frequency dependent

The thermal dissipation and optical power function of equation 3 and the ω of equation 2 are frequency dependent and determine the frequency response of the system. The optical power function is the frequency spectrum of the light source. For instance, a perfect sine modulated light beam with a frequency of 500 Hz has a flat response except for one peak at 500Hz. In this research the light beam will be modulated with an optical chopper which produces (approximately) a square wave. The optical power function of a square wave is a sinc function.

2.2.4.1 PRESSURE FUNCTION

The sound pressure of the produced waves decreases with one over the angular velocity in the frequency domain, as shown in equation (2). When an optical chopper is used r material, the light intensity will be modulated like a square wave. Integration of this signal over one period will give the amount of energy which is used to heat the material. The first half period the absorber will heat up and the second half it will cool down. On every modulated frequency the amplitude of the light will be the same but when the frequency increases, the period decreases and so will the heating time. When the frequency is doubled only half the energy is available to heat the absorber material for each period. This results in only half the temperature increase (and thus sound pressure) for each period, which will result in a 6 dB signal decrease.

Explained in a more mathematical way; the temperature of the material is proportional to the integral over the light intensity in the time domain. This is equal to dividing by the angular frequency in the frequency domain.

2.2.4.2 Thermal dissipation

In calculating the frequency response, the heating of the absorber cell was assumed to behave adiabatic. When applying this assumption for really low frequencies (<10Hz) this should result in very high temperatures and sound pressures, because the heating period is relatively long. Of course this doesn't happen, because the major part of the heat dissipates in the absorber material and into the cell wall. The process of heat dissipation can be simulated with the (one dimensional) heat equation (4).

$$\frac{\partial T}{\partial t} - \alpha \frac{\partial^2 T}{\partial x^2} = 0 \qquad (4)$$

The simulation is done in MATLAB with the finite element method and contains 50 elements. The first element is the element that receives the heat from the light beam and the last (50th) element has constant temperatures which represent the wall of the cell. The script calculates temperature differences between the elements and the resulting heat flux for each loop iteration. The MATLAB script and a short explanation can be found in appendix 1. In figure 7 four heat profiles are simulated on different frequencies. The different lines represent the heat profile on different moments in time.

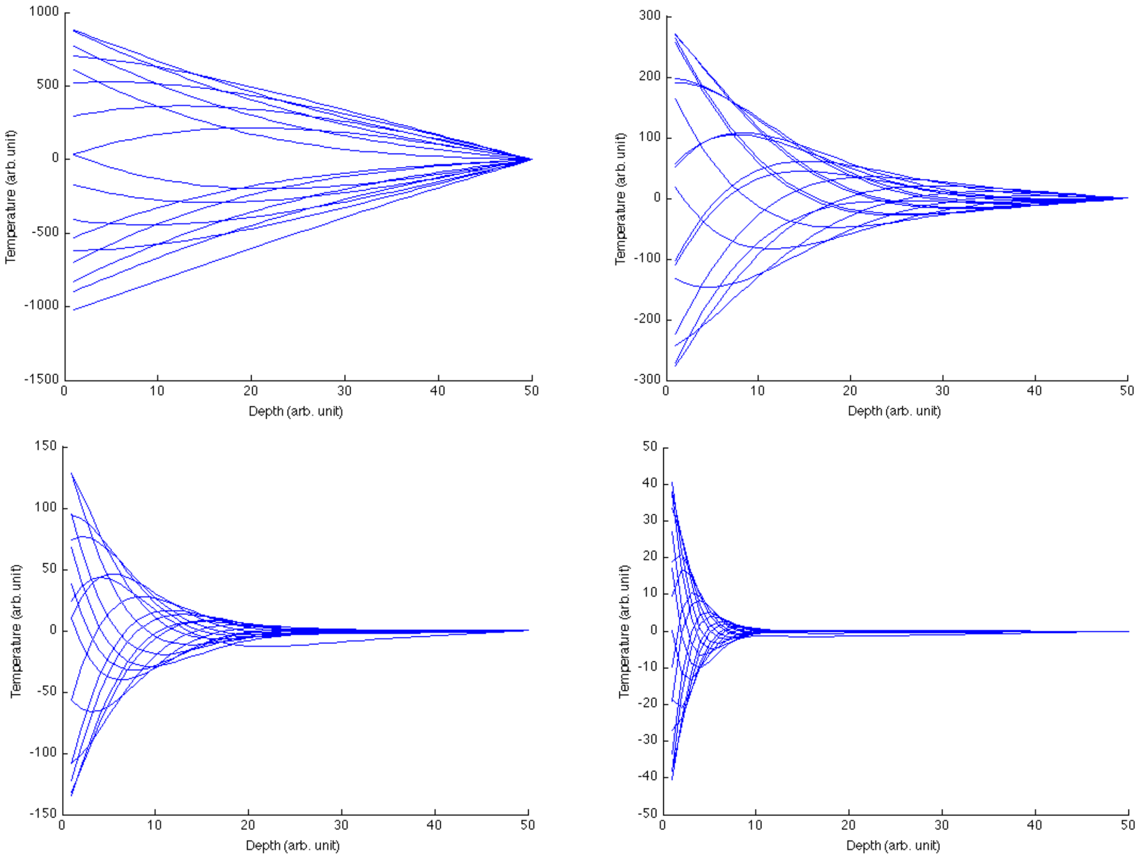


Figure 7 - Heat profiles for different frequencies (upper left is low, lower right is high)

The upper left heat profile shows a temperature profile with a large slope, which means a lot of heat is transferred to the cell wall. The lower right heat profile shows an almost flat temperature profile after element 15, which means almost no heat flux is present. On frequencies of this profile and higher, the absorber heating could be treated like an adiabatic process.

Summarizing, the thermal dissipation function gives the fraction of heat in the absorber that is used to heat the absorber surface and therefore is not dissipated to the cell wall or the material. For low frequencies this is close to zero and for high frequencies close to one.

To calculate this function, Kleinman uses the *thermal relaxation time*. This is the timespan it takes for the heat from a laser pulse to dissipate to equilibrium. This equilibrium is defined as the point at which 50% of the heat is dissipated in the material and 50% used to create a temperature difference at the surface. Figure 8 shows the function G_ω plotted versus the thermal relaxation time multiplied by the frequency. When this product is 1, the value of the thermal relaxation time is equal to the period of the modulation frequency. In the graph is visible that the value of $|G_\omega|^2$ is around 0.25 for $\omega\tau = 1$, so the value of G_ω is 0.5. This means 50% of the heat is transferred into material and to the cell wall.

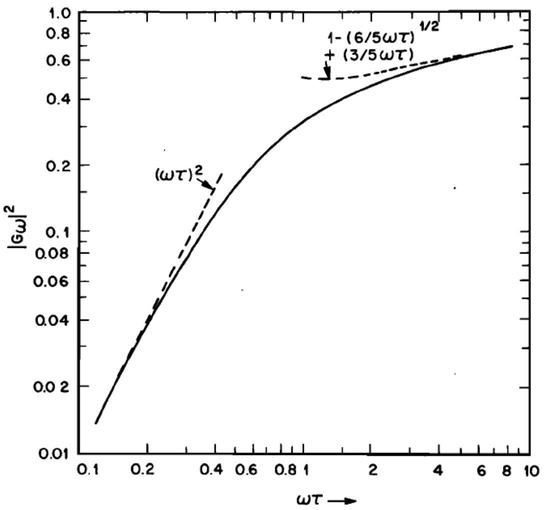


Figure 8 - Dissipation function Gw [3]

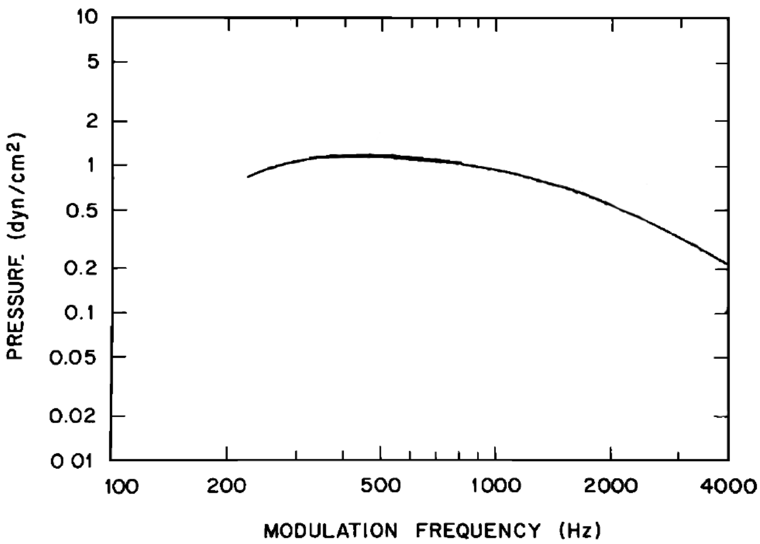


Figure 9 - Simulated frequency response by Kleinman [2]

2.2.4.3 COMBINATION OF PRESSURE FUNCTION AND THERMAL DISSIPATION

The combination of pressure function and thermal dissipation function result in a peak in the frequency response. For the low frequencies the signal will decrease to zero, for the high frequencies the signal will also decrease to zero with one over the frequency. If thermal relaxation time is shorter, because of a more bulky absorber or a higher thermal conductivity, the peak will shift to a higher frequency. When the absorber has a better adiabatic behavior, the peak will shift to a lower frequency. Figure 9 shows the combined frequency response simulated by Kleinman.

2.3 Experimental results

2.3.1 Research setup

To measure the four key research topics, a more flexible setup is needed than the glass jar used in the introduction experiment. A picture of the setup is shown in figure 10. The setup is build using the following components:

- 200 mW - 660 nm laser diode (unknown brand)
- Variable power source to vary intensity of the laser diode (Delta Elektronika, E018-0.6D)
- Optical chopper with frequency range 0-3600 Hz (Stanford Research Systems, SR540)
- Two positive lenses (18 mm and 100 mm) to create a beam expander for laser safety
- Optical table to mount the light modulation setup
- Mirror to project the light on the receiver capsule
- Microphone and power supply to record the sound (see appendix 2)
- Foam to isolate the receiver capsule and microphone from vibration on the table
- Simple audio mixer to amplify the microphone signal (Behringer UB1202FX)
- Laptop with a spectrum analyzer (iSpectrum[3])

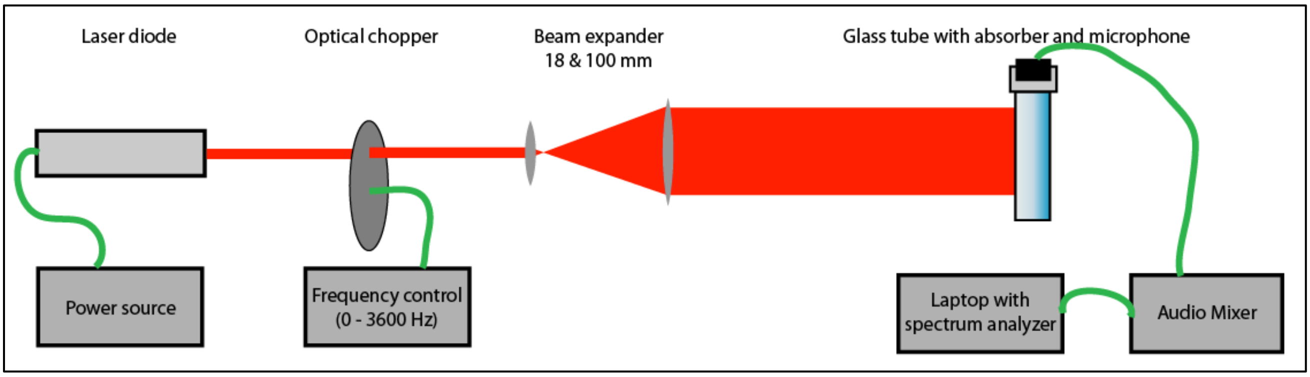


Figure 10a – Sketch of setup

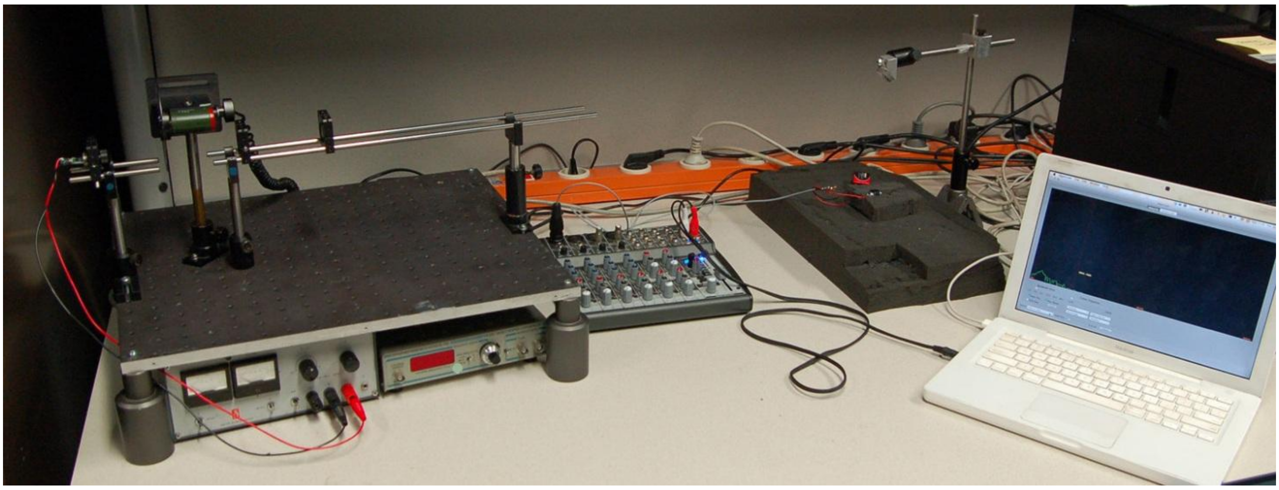


Figure 10b – Picture of setup

[3] http://www.dogparksoftware.com/iSpectrum.html

2.3.2 Absorber material research

The first step in this research part is the selection of an optimal optical absorber material. Two groups of absorbers are tested. The first group contains black carbon based materials and is expected from literature to give the best results.

- Lampblack was found by Bell to be the best material
- Charred cotton was used by Kleinman as best material
- Laser printer toner was used because it has a comparable structure as the other two (small carbon particles)

The second group contains absorbers that do not match the optimal material characteristics. These materials are expected to give a suboptimal response, but could be interesting to measure as comparison.

- Indian ink (black) applied to paper and a piece of thick transparent plastic.
- Black cardboard
- Black cotton (comparable structure to charred cotton, but not charred)
- Heat-shrink tubing

The measurements are done with a chopper frequency of 250 Hz, 500 Hz and 1 kHz, in a glass cylinder with a volume of 3.5 ml with 200 mW optical power. For all measurements background noise was at least 10 dB lower, so no measurement influence is expected.

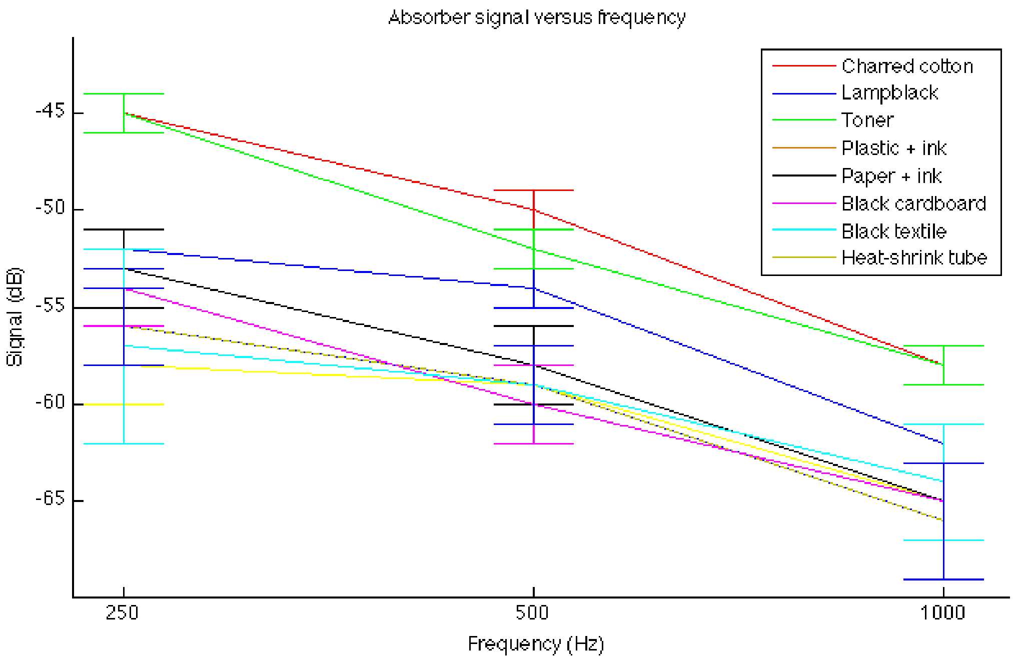


Figure 11 - Absorber responses

The results are plotted in figure 11. The first three pure carbon based materials indeed gave the best results. The indian ink performed slightly better on paper than on plastic. Furthermore, on some absorbers the effect of thermal dissipation is visible on a higher frequency than others. Heat shrink tube, plastic with ink and lampblack seem to have a faster thermal relaxation time, so the signal decrease for low frequencies starts on a higher frequency. Overall a gain of more than 10 dB can be reached by choosing a good absorber material like charred cotton.

2.3.3 Absorber cell volume research

The research on the cell volume is performed with a glass tube with the same inner diameter as the microphone (10 mm), so a closed volume is created (as shown in figure 12). By sliding the position of the microphone the enclosed volume can be varied. Measurements are done on an interval of 1 cm, charred cotton is used as optical absorber and the chopper was set at a modulation frequency of 500 Hz. At this frequency the acoustic wavelength is 68 cm, so an uniform pressure distribution is assumed throughout the volume.

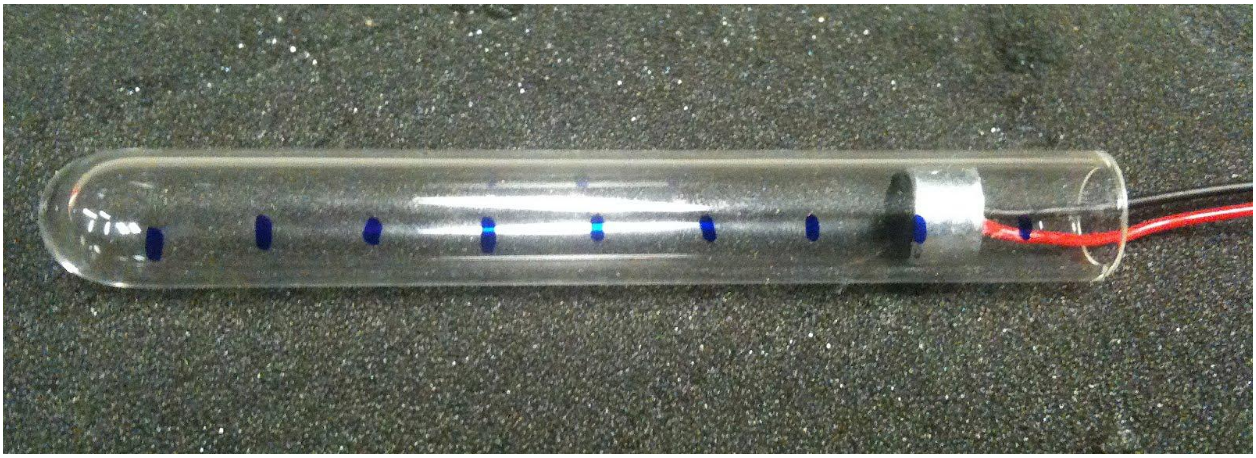


Figure 12 – Variable volume

According to the theoretical analysis, the signal should decrease with 6 dB on every doubling of the volume. In figure 13 the signal is plotted versus the $\log_2$ of the volume. A linear fit is done with least square method and gives a decrease of -6.98 dB (+/- 0.59 dB). Large error bars are due to the fact that it is quite difficult to get similar optical absorbance for every measurement. In each volume step the strongest signal was tried to achieve.

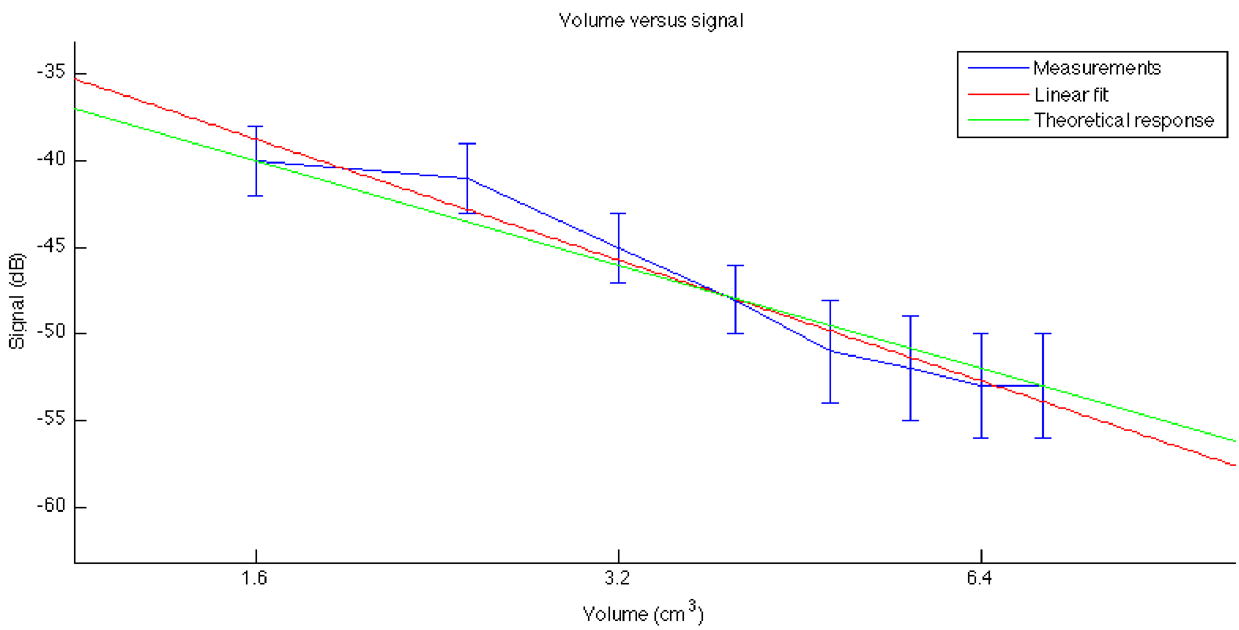


Figure 13 - Signal versus volume

2.3.4 OPTICAL POWER RESPONSE

To measure the influence of a change in optical power, first the actual output of the laser diode has to be measured. The output of the laser diodes can be controlled by altering the voltage of the power supply. The light beam is chopped at 1 kHz, dimmed with a 90% Neutral Density (ND) filter and measured with a photodiode connected to an oscilloscope. The ND filter is placed to protect the photodiode from damage by burning due to the 200 mW laser beam. The oscilloscope is triggered by the chopper and measures the amplitude of the signal. At the nominal operating voltage (5 Volt) a reference measurement was done, which represents 100% output of the photodiode.

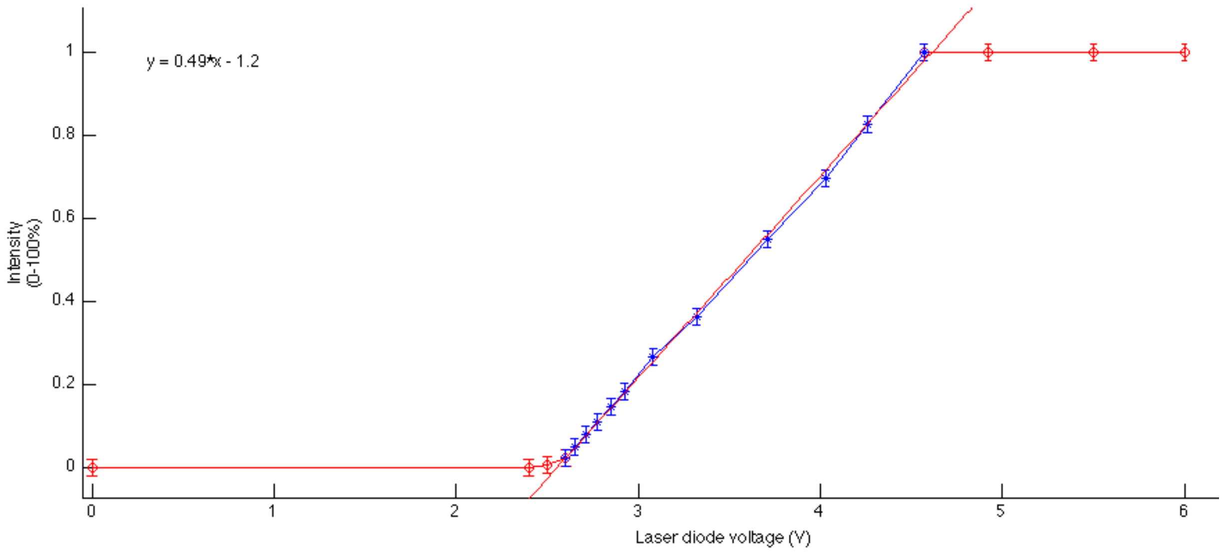


Figure 14 - Laser diode output versus voltage

The relative amplitude of the photodiode signal is plotted in figure 14. It shows a linear relation after a threshold voltage of around 2.6 Volt. The laser diode seems to have a protection circuit that limits current above an input voltage of 4.6 Volt. With a linear fit, using only the measurements above 2.6 and below 4.6 Volt, the relation between diode voltage (V) and intensity (I) of equation (5) can be derived.

$$V = 2.06 * I + 2.56 \tag{5}$$

The error margins are determined with the least square method. The error is $2.07 * 10^{-2}$ Volt for the slope and $9.9*10^{-3}$ Volt for the offset. These values are assumed to be small enough to neglect.

With use of equation (4) the relation between laser output and sound pressure can be measured. To determine the signal increase every time the intensity doubles, the $\log_2$ of the intensity is plotted versus the signal. The measurement is done at 1 kHz chopper frequency and with the 3.5 ml cell filled with charred cotton. The measurements are plotted in figure 15.

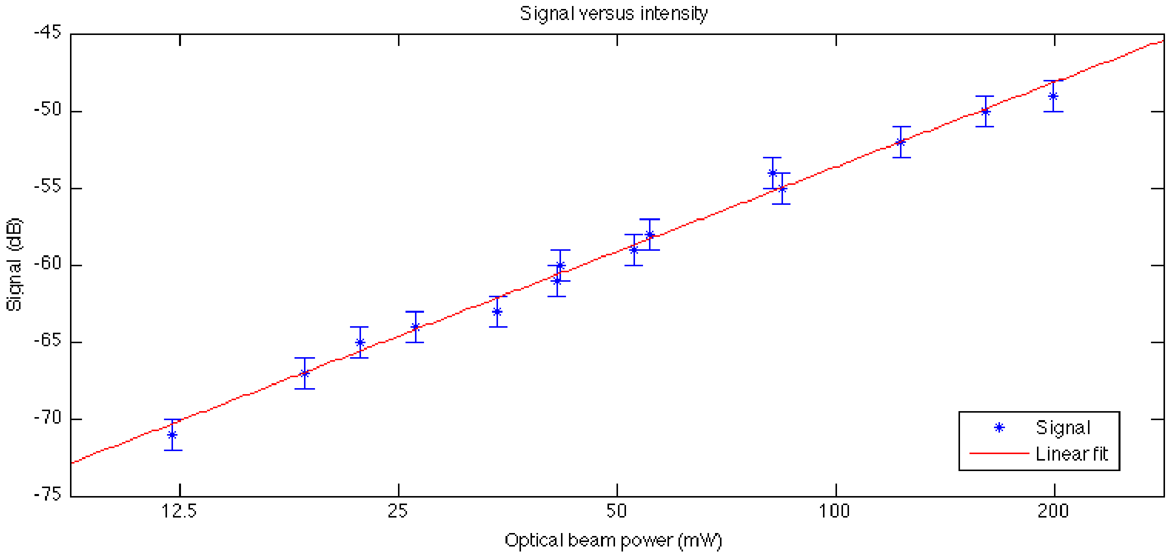


Figure 15 - Signal versus optical power

From literature explained in paragraph 2.2.3, the graph is expected to increase with 6dB for every doubling of the optical power. The graph in figure 15 shows a linear increase of 5.50dB (+/- 0.14) every time the optical power doubles. An increasing deviation (like in the Kleinman measurements) from the theoretic model is not visible but both graphs are not directly comparable due to different cell sizes and light intensity.

2.3.5 FREQUENCY RESPONSE

The frequency response is determined of the setup with the 200 mW laser diode at 100% intensity, the optical chopper and the 3.5 ml glass tube filled with charred cotton fiber. Because the optical chopper and some cooling equipment in the lab create a lot of background noise, for each frequency both signal and background noise are measured. For low frequencies (<100 Hz) the signal is very close to the noise level and measurements might be unreliable. For high frequencies (>2500 Hz) the noise of the chopper disturbs measurements. The result is plotted in figure 16.

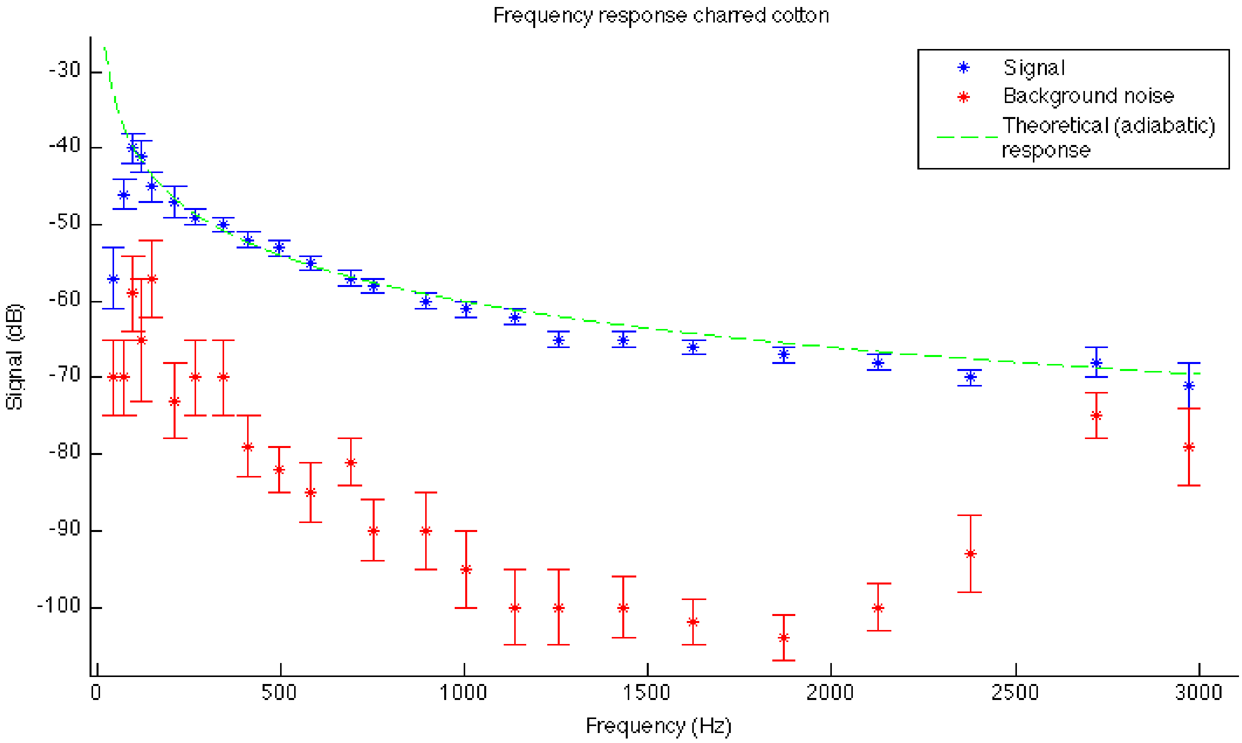


Figure 16 - Frequency response of charred cotton

As expected from the theoretic analysis, explained in paragraph 2.2.4, the signal decreases roughly with one over the frequency for the adiabatic response (equation 2). Because the signal axis is in dB-scale, the 20*$\log_{10}$ of one over the frequency is plotted as theoretical response. The optimal (thermal) response is around 100 Hz, which is at a much lower frequency than the Kleinman measurements. This is probably because the large volume of the glass tube provides much more insulating air than the 1 mm^3 volume used by Kleinman. This results in a better adiabatic behavior of the absorption material.

2.4 DISCUSSION

Response of different absorber materials was according to our expectations. Materials that matched the optimal absorber characteristics best (dark color, porous structure and low heat capacity), gave the best performance. Materials that are expected to have a higher thermal conductivity showed lower response on the 250 Hz measurement. This agrees with the frequency response theory. The best absorber for the demonstration setup will be charred cotton, as expected from Kleinman literature.

The influence of the absorber volume was roughly as expected. No big deviations were expected, because it should give a completely linear response according to the ideal gas law. Deviations in the response are due to measurement and setup errors. The research can be concluded with the notion that smaller volumes give a higher response but optical alignment (to reach a constant optical utilization factor) gets significantly more difficult on smaller volumes.

The optical power response was a little lower than expected from theory and the air heating model of Kleinman. Both measurements by Kleinman and in this report show a deviation from the air heating model. It is difficult to compare these because another graph scale and setup is used. A clear explanation for the deviation cannot be given, but as Kleinman already mentioned: 'The charred cotton is an incompletely understood component in the system'. This implies that there is probably some physical effect not included in the model.

The frequency response showed a decrease in signal according to the theory. The optimal frequency was at a much lower frequency than in literature from Kleinman. This is probably due to the fact that Kleinman used a 1 cubic millimeter absorber cell. In this cell the absorber material is very close to the constant temperature cell wall and the thermal relaxation time is much lower. The measured charred cotton fiber was placed in a much larger cell with a lot of isolating air between cell wall. This gives an adiabatic response upon much lower frequencies.

The measurements roughly agree with theory, but all have a deviation from the theoretic analysis. The errors and deviations are mainly due to the fact that relatively simple equipment was used. Also consistent optical alignment and coupling to the absorber material was hard to achieve. However, for this research this is not an issue, because measurements are mainly intended to illustrate the theory and create a feeling with the subject. For advanced absorber research, a more sophisticated setup should be used.

3. LIGHT INTENSITY MODULATION

Chapter two showed the possibility of making the modulated light audible. However, the only option so far was to produce square wave modulated light with the optical chopper. To transfer and receive speech, a more sophisticated modulator is needed. This chapter will treat the selection of a suitable light source, a theoretical analysis on modulating with sound waves, experimental measurements and a discussion of the results.

3.1 LIGHT SOURCE SELECTION

The original photophone setup used the sun as light source. This was an obvious choice, because around 1900 the electric light sources were not small and powerful enough to create a parallel beam with a high intensity. For research purposes the sun is not the most practical light source, so an alternative should be found.

3.1.1 LIGHT SOURCES

For the demonstration model the light source has three requirements:

1. The light source has to be able to create a parallel beam, to make transmission possible over at least 10 meters distance.
2. The light beam has to have at least 100 mW continuous power, to make the photoacoustic effect clearly audible with the current absorber cell and without electronic amplification.
3. The light beam intensity must be safe to use without eye protection.

The most suitable light source is a laser diode. These are small, cheap and produce a powerful parallel beam in the range from a few milliwatts to several watts.

3.1.2 LASER SAFETY

Safety is a problem in using a laser diode as transmitting beam. Because the light is parallel, the eye will focus the beam on a very small spot on the retina and damages or burns it. To create a beam with safe intensity, the diameter of the beam is expanded with a Keplerian beam expander. The power used in most laser pointers (1 mW) is considered to be reasonably safe. The diameter of the pupil is about 5 mm in normal conditions, so the maximum intensity is roughly 1 mW per 20 mm^2. The intensity of the beam will be modulated between 0 and 200 mW, so average intensity will be 100 mW. For 100 mW average power the area should be 2000 mm^2, which requires a beam diameter of 50 mm for safe intensity.

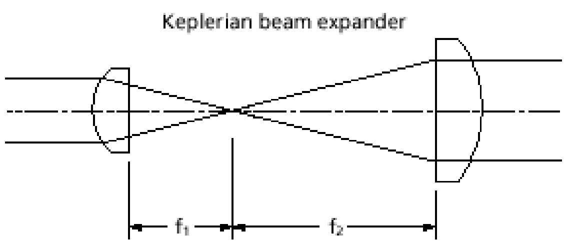


Figure 17 - Beam expander

In this calculation the intensity distribution is assumed to be homogeneous (instead of Gaussian) and the modulation exactly around 50% intensity. For lab use these assumptions are sufficient, but for the demonstration setup a safer margin should be used.

3.2 Modulation Theory

To modulate light intensity with audio waves and without the use of electronics, the sound waves have to be converted into mechanical movement. The most practical way to do this is using a vibrating membrane. The movement of a membrane due to the pressure waves can be explained in four steps:

- A sound pressure wave consists of small deviations from the atmospheric pressure
- When sound waves hit a membrane, a pressure difference arises between the front and the back side of the membrane
- By this pressure difference a force (pressure difference times area) is exerted on the membrane
- The exerted force results in movement of the membrane

The amplitude of the membrane movement can be simulated using the equation of a mass-spring system (equation 6). The equation has the constants *m* (mass), *c* (damping) and *k* (spring) and is driven by the force *F(t)*. When the frequency response of the equation is plotted, a typical graph like figure 18 is produced.

$$F(t) = m\frac{d^2x}{dt^2} + c\frac{dx}{dt} + kx \tag{6}$$

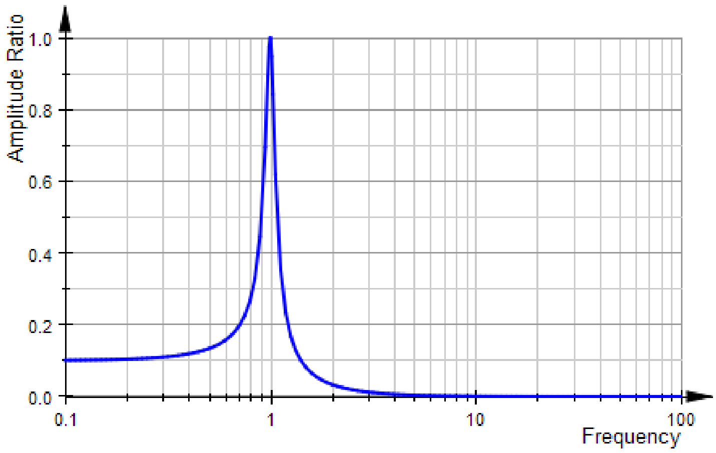


Figure 18 - Typical frequency response plot

In this graph three regions are visible;

- The left side of the peak shows constant amplitude for low frequencies. In this part the response is based on the spring constant. The exerted force results directly in an excursion of the membrane.
- The peak is the resonance frequency of the system. In this part the excursion will be determined by the damping.
- The right side is decreasing with one over the square of the frequency. In this part the response is mass based. The force will result in an acceleration of the mass of the system.

For the light modulating system the resonance frequency should be avoided and best response is expected with a spring based membrane response (the left part of the graph). For this range the frequency response is relatively flat.

3.3 MODULATION TECHNIQUES

After the pressure waves are converted into mechanical movement, using the membrane response described in the previous paragraph, this movement has to modulate the light beam intensity. In the past decades several techniques are developed and successfully used to transmit speech to an electronic receiver. For the photoacoustic receiver at least 50 mW of modulated light is needed. This determines the need for at least 25% light modulation when using the 200 mW diode laser. A selection of possible techniques is summarized in this paragraph.

3.3.1 BENDING MIRROR

The bending mirror method is the oldest technique and was used in Bell's original setup. In this setup a thin mirror is used as membrane. Due to the pressure waves, the mirror bends and converges or diverges the light as showed in figure 19. A larger divergence results in a lower light irradiance on the receiver and vice versa.

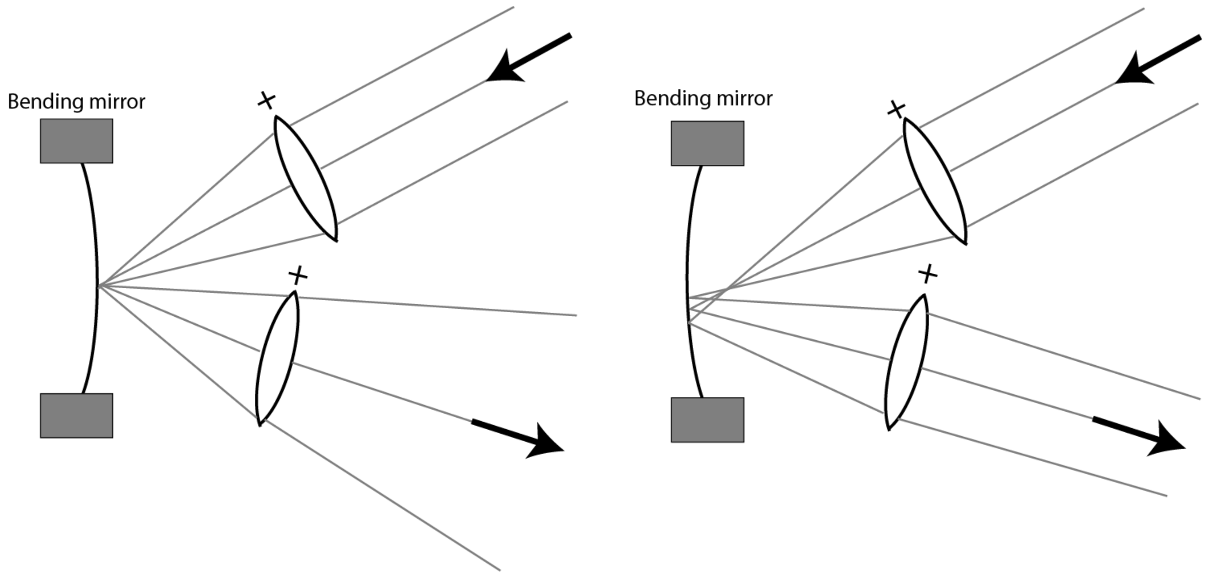


Figure 19 - Bell's modulation setup

A large advantage of this setup is the flat (spring-based) response of this system, because of the high stiffness of a mirror. However, in these drawings the effect is heavily overdone, but in a real setup the bending of the mirror is very small (< 1 mm, depending on the stiffness of the material). This results in a maximum beam modulation of a few percent, which is sufficient for an electronic receiver but not for the photoacoustic receiver. To compensate this, a more powerful beam should be used.

3.3.2 VIBRATING KNIFE

The second modulation technique was also invented by Bell. There are two versions of this setup, but both are based on the same phenomena. In Bell's setup the light beam passes two grids with a number of small slits. The first has a fixed position and the second is connected to the membrane, transferring the vibrations from the membrane to the grid. The orientation of the second grid with respect to the first grid determines the amount of light that passes, as shown in figure 20.

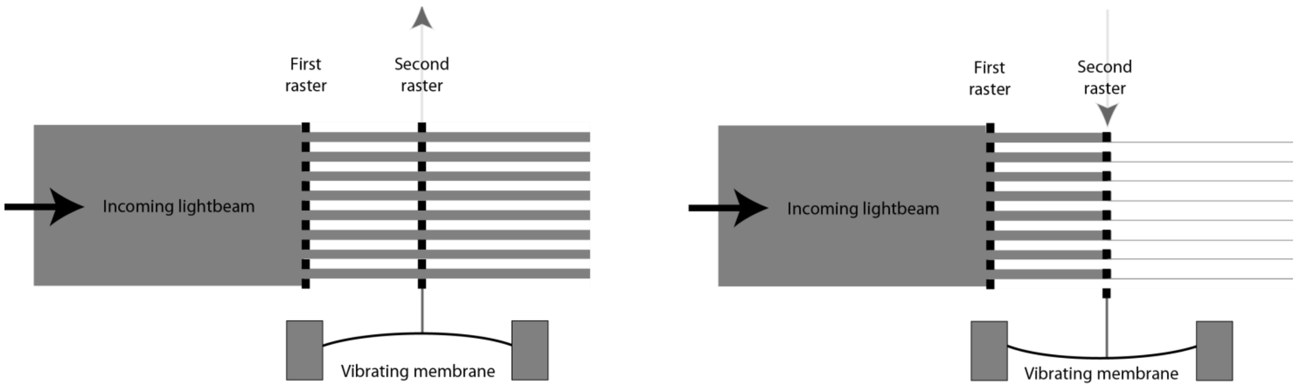


Figure 20 - Raster modulation

This setup can modulate the light beam between 0 and 50% intensity, for optimal membrane amplitude. Because membrane amplitude is very small, a raster with small slits is needed. Another problem is the mass of the vibrating grid, which makes the system behave like a mass controlled system (as explained in the previous paragraph). This results in very low modulation for the higher frequencies.

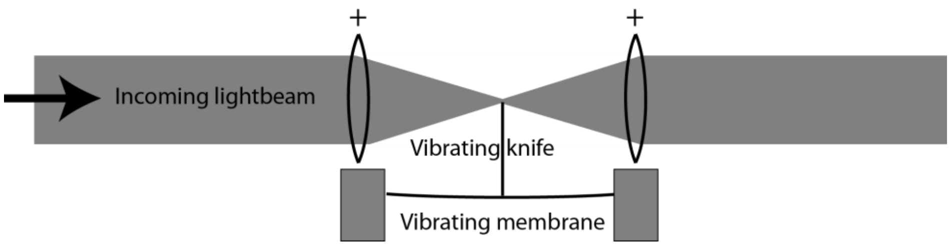


Figure 21 - Vibrating knife method

Because this setup is using a parallel laser beam, a simpler version of this setup can be build. In this setup the beam is focused and a knife connected to the membrane is placed in the focal point (as shown in figure 21). Because the focal point can be made very small, the sensitivity of this setup is much higher than the grid setup. Also the setup can modulate the incoming beam between 0 and 100%, which doubles sensitivity compared to the grid method.

Because of the extremely high intensity in the focal point, the knife has to be made from steel or another heat resistant material. Because this knife will have a relative high mass comparing to the membrane, it will give the system a mass based frequency response.

3.3.3 ROTATING MIRROR

The vibrating knife systems are expected to have a mass based frequency response, which makes modulation of higher frequencies quite difficult because of the $1/\omega^2$ falloff. By designing a system that is based on rotation of the modulation piece instead of movement, less mass acceleration is needed. This will make the system behave more like a spring based system with a flat frequency response. The inspiration for this approach was found in the work of Professor Rankine [7], whose setup is showed in figure 22. Basically this setup is the same as the vibrating grid method of the previous paragraph, but now both grids are fixed. The varying angle of the mirror creates the modulation at the second grid.

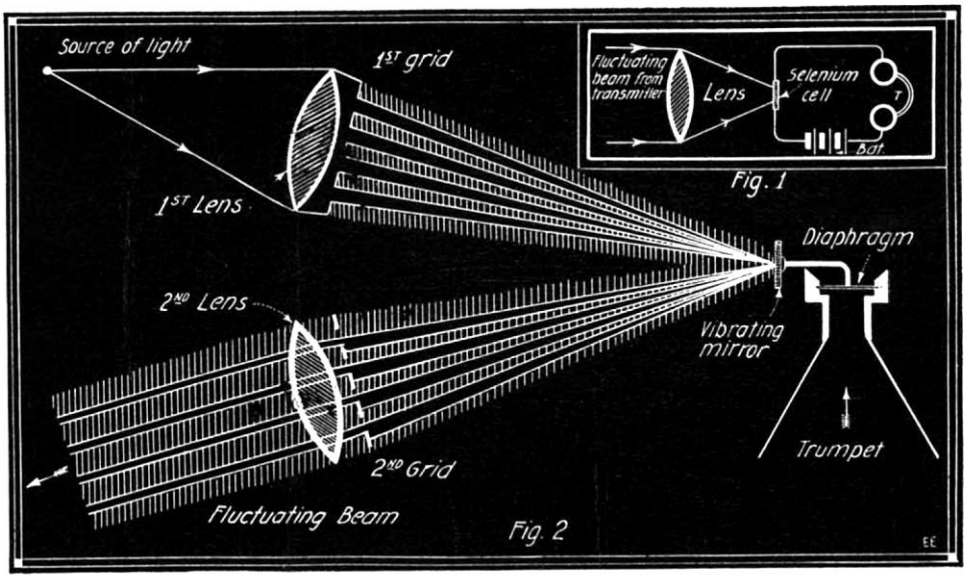


Figure 22 - The Rankine setup with rotating mirror [7]

As in the vibrating knife setup, the use of a laser beam creates the possibility to simplify the setup. In figure 23 the simplified setup is shown. The mirror is rotated by the bending of the membrane, which modulates the reflection angle of the beam. This beam is projected on an optical knife that blocks the beam, depending on the angle of reflection.

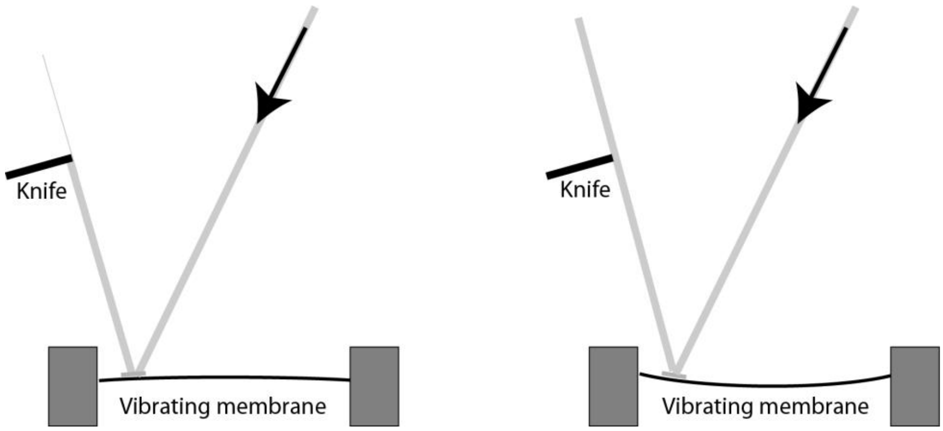


Figure 23 - Rotating mirror

The sensitivity of this setup can be adjusted by changing the distance between the mirror and the knife. For high sensitivity a perfect flat mirror is needed, because otherwise the reflecting beam won't be parallel and the modulation effect of the knife won't be optimal. Theoretical a 100% intensity modulation can be achieved with this setup.

3.4 EXPERIMENTAL RESULTS

3.4.1 EXPERIMENTAL SETUP

All three modulation techniques are usable for modulation of light and have been proven in literature to function with an electronic receiver. However, for use with the photo acoustic receiver at least 50 mW of AC-signal is needed, so the major part of the 200 mW incoming beam should be modulated. For this reason measurements are only done on the vibrating knife and rotating mirror technique.

Measurements are done with a photodiode connected to an oscilloscope. The photodiode is preferred over the photo acoustic receiver for three reasons. It has a much higher sensitivity, it is not influenced by the sound produced by both the modulation setup and the background noise and it has a flat frequency response in the audible frequency range. The goal of the measurements is to determine the modulation depth of the setup. The optical chopper is used to measure the reference amplitude for 100% modulation depth. All measurements are normalized to this value in order to give a percentage of modulation.

Two setups are built as extension of the original setup used in chapter two. For the vibrating knife method, the setup of figure 21 is built with the following parts. A picture of the setup is shown in figure 24.

- Speaker coil, stripped from an old speaker
- Cardboard and a thin steel knife (0.04 mm thick) attached to the speaker coil
- Function generator to drive the speaker (HP 3310B)
- Amplified photo diode (Newport, 2001-FC)
- Oscilloscope (Tektronix, TDS-210)

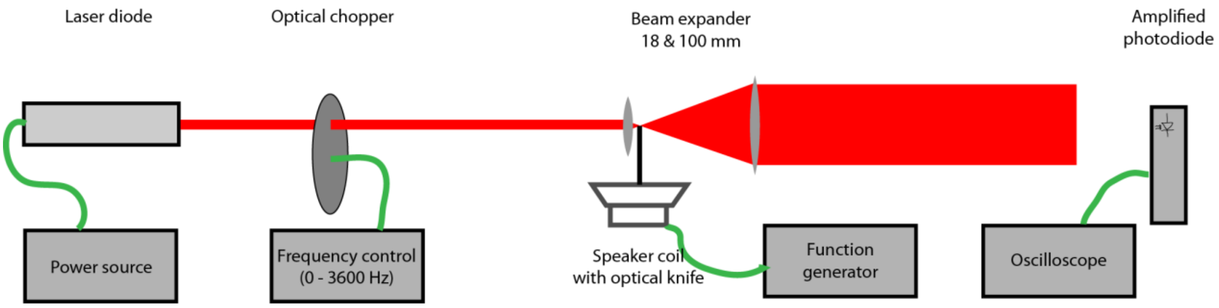


Figure 24a – Diagram of vibrating knife setup

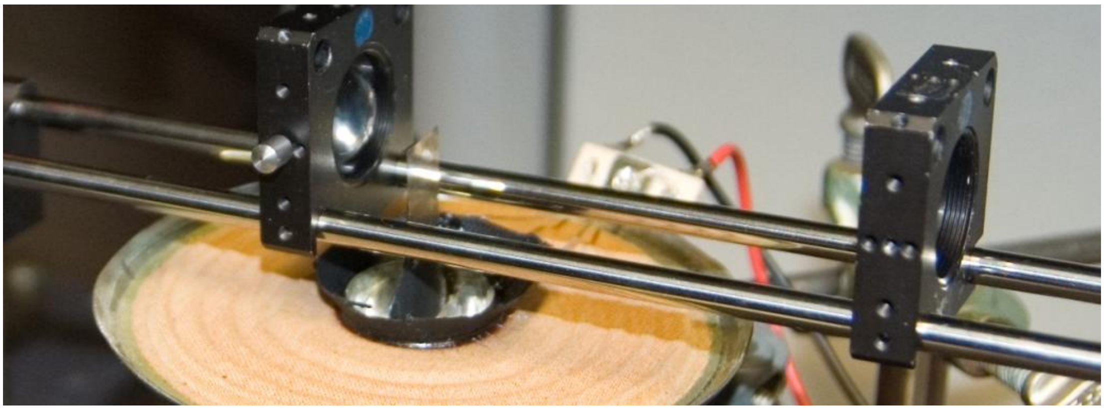


Figure 24b – Picture of vibrating knife setup

For the rotating mirror method, the setup of figure 23 is built with the following components. A diagram and pictures are showed in figure 25.

- Plastic cylinder with a diameter of 3 cm
- Latex membrane made from latex gloves mounted with a tie wrap
- Small piece of thin metal (0.04 mm), acting as a mirror
- Small speaker as audio source
- Function generator to drive the speaker (HP 3310B)
- Amplified photodiode (Newport, 2001-FC)
- Oscilloscope (Tektronix, TDS-210)

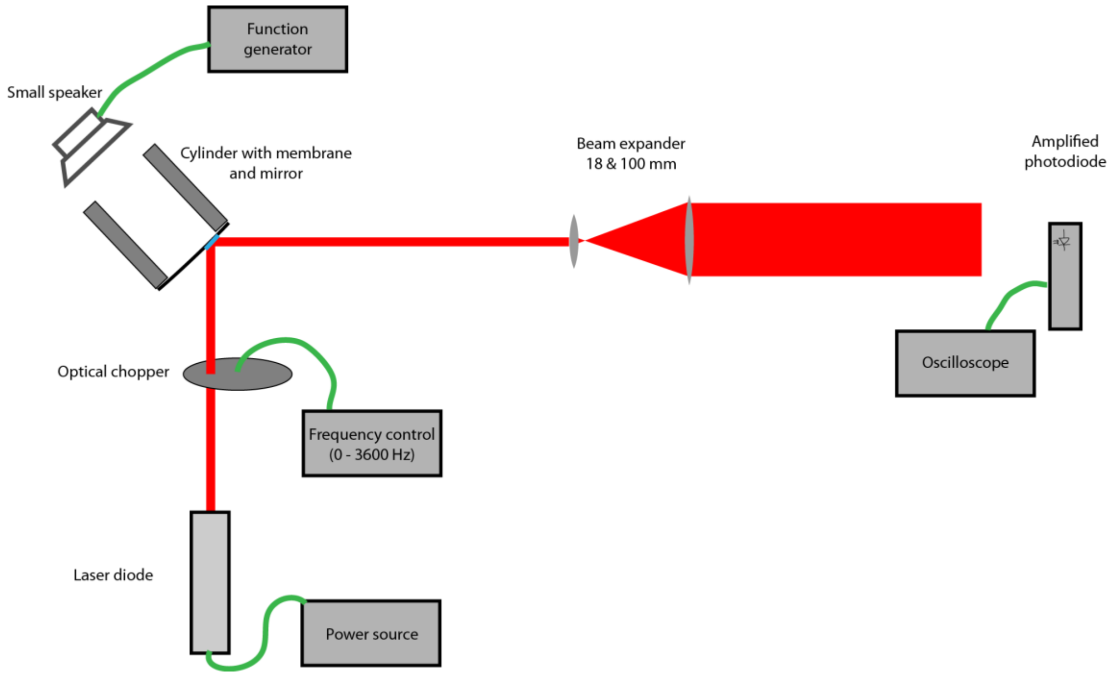


Figure 25a – Diagram of rotating mirror setup

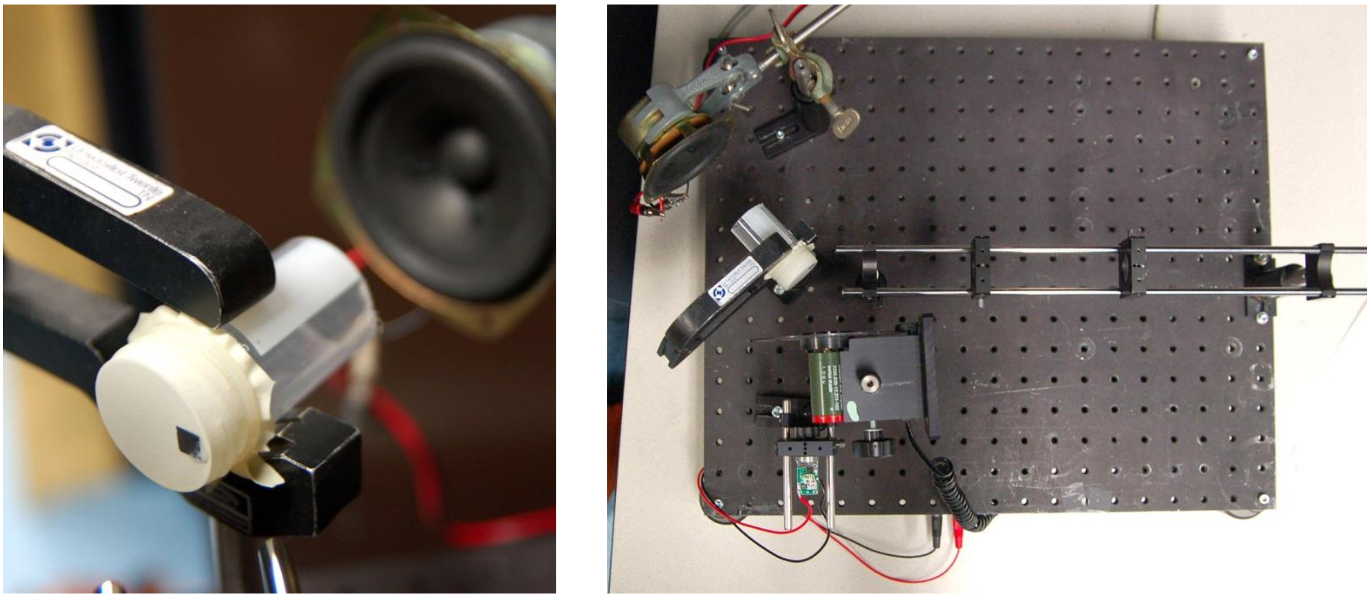


Figure 25b – Pictures of rotating mirror setup

3.4.2 VIBRATING KNIFE MEASUREMENTS

The vibrating knife setup is expected to behave like a mass based system, except when a very stiff membrane is used. Although this will result in a very small excursion so the modulation depth will be very low. The most practical way to setup this system is to attach the optical knife directly to the coil of a speaker unit without membrane. The results of measurements should be comparable to a knife attached to a membrane. The only physical difference is that in this setup the force on the mass is created by an electromagnetic force instead of a pressure difference. The speaker coil will add some extra mass to the system, so the resonance frequency will shift to a lower frequency.

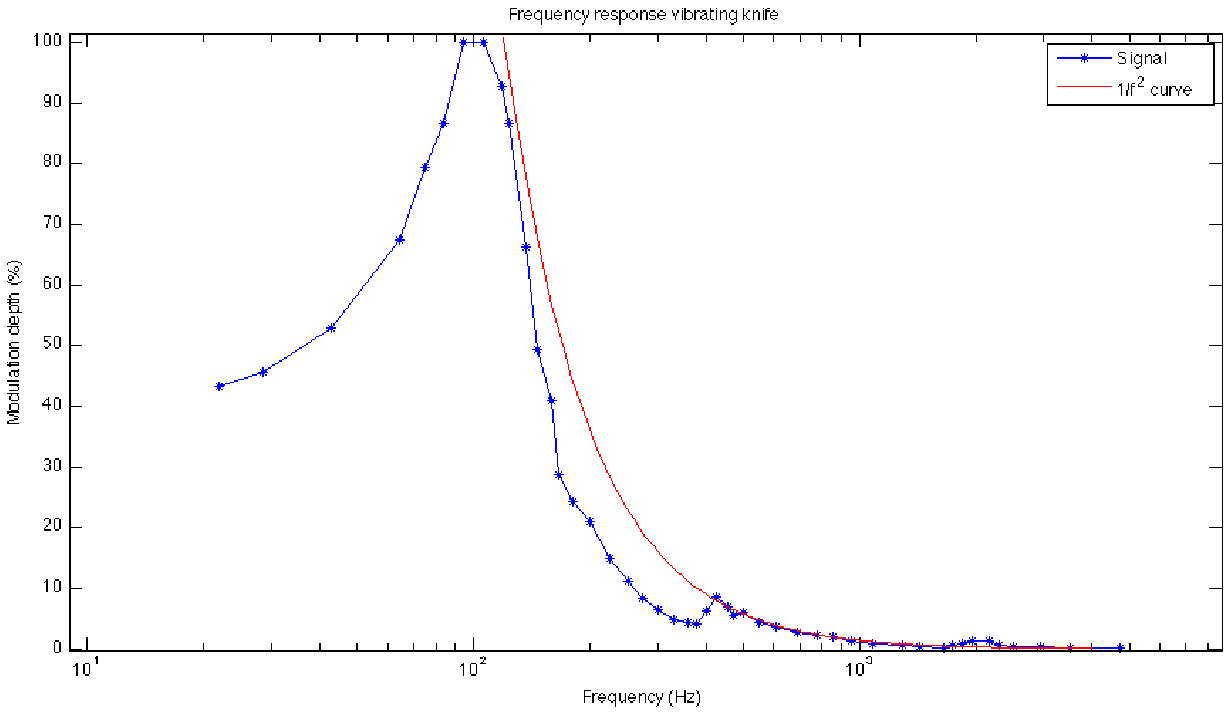


Figure 26 - Frequency response vibrating knife

The response (plotted in figure 26) shows a graph as expected from literature. Around 100 Hz there is a resonance peak, on the left side the modulation depth slowly decreases to 40% and on the right side modulation depth decreases rapidly to zero. There are some small resonances visible around 450 Hz and around 2000 Hz. In red a curve with the slope of one over frequency squared is drawn. This curve roughly matches with the measured curve.

To check if audio transmission is possible with this setup, an audio source is connected to the coil of the speaker and a (digital) high-pass filter (>200 Hz) is applied on the audio output to reduce the effect of the resonance peak. The photodiode output is amplified and connected to a headset. Transmitted speech and music are clearly audible with this setup, however high frequencies are weak.

3.4.3 ROTATING MIRROR MEASUREMENTS

The rotating mirror setup is built with a 3 cm diameter cylinder with a piece of latex (from latex gloves) as membrane. On the membrane a very thin piece (0.04 mm thick) of metal is glued as mirror. A small speaker is placed on the backside of the membrane and is driven by a function generator. No knife is used, because the boundaries of the photodiode housing act already as a knife, so the use of a knife makes no difference. The measurements are plotted in figure 27.

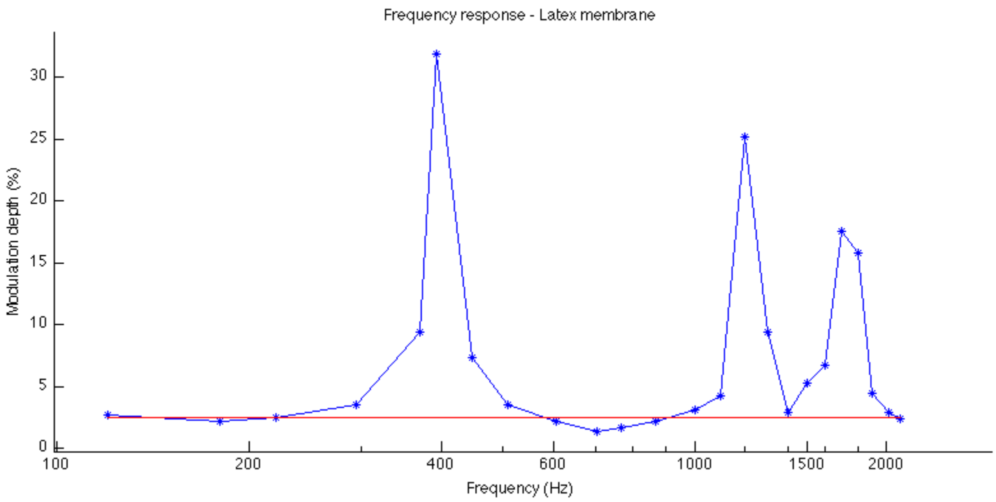


Figure 27 - Rotating mirror measurements

The plot shows a baseline modulation of around 2.5% and three large resonance peaks around 400 Hz, 1200 Hz and 1700 Hz.

Also with this setup the ability to transmit audio is tested. Audio played on the speaker is clearly audible when a headset is connected to the photodiode. Also speech from a distance of 0.5 meters from the membrane is audible. The membrane setup acts like a sensitive microphone.

3.5 Discussion

The vibrating knife setup is behaving as expected. The setup has a large resonance peak around 100 Hz, with a flat response on lower frequencies and is decreasing with one over frequency squared for higher frequencies. The response is not perfectly smooth, which probably is caused by some small resonances in the setup. Modulation depth is good enough for the photo acoustic receiver up to 200 Hz but is too small for higher frequencies. The modulation depth will be even worse if a membrane was used instead of the speaker coil.

Modulation depth could be increased if the focal point could be made smaller, but with the used optics, laser source and alignment options this was quite difficult. The resonance peak could shift to a higher frequency by decreasing the mass of the setup or an increase of the spring constant. However, increase of the spring constant will result in lower amplitude and less modulation depth.

The rotating mirror setup is partly behaving like expected, according to the baseline modulation depth of 2.5%. The three large resonance peaks were not expected. Probably these are resonant modes in the membrane, caused by the flexibility of the latex membrane and the relative high weight of the mirror. A higher spring constant of the membrane and a lighter mirror could solve this problem but modulation depth would become smaller. The modulation depth can be increased by increasing the distance from the mirror to the knife. However, when increasing modulation depth, the resonance peaks cause the signal to be out of modulation range. This means that the beam angle variation is too large to result in a smooth intensity modulation between 0 and 100%, which results in a clipped waveform. The clipped waveform will result in a highly distorted signal.

For long distance communication (>100 m) the vibrating knife is technically superior to the rotating mirror. The small varying angle of the beam will result in a large movement of the beam at large distances. For example, 1 mm movement at 10 cm distance will result in 1 meter movement on 100 meter distance. To capture the complete beam intensity, a large parabolic mirror is needed. The vibrating knife uses a fixed beam, so in the ideal case communication distance is unlimited.

4. DEMONSTRATION SETUP

4.1 RESEARCH RESULTS

From both research parts can be concluded that the setups are working, but sensitivity is rather low. The experimental receiver cell needs at least 50 mW of AC signal to produce audible sound levels. For demonstration purposes this should even be higher, because it will probably be used in noisy ambiances. The modulation part could create a modulation of roughly 5% when setup is optimized, which results in 10 mW of AC signal from the 200 mW light source. To create a working demonstration setup a much stronger light source is needed or both sender and receiver should be significantly optimized.

The use of a much stronger light source (for instance 2000 mW) is not safe to use and also very impractical. That amount of power focused on a small part of the modulation setup will probably burn of melt most materials. Heat resistant materials are usually heavier, which will result in less modulation depth.

To optimize the modulation depth, research should be done on the behavior of vibrating membranes and lighter knives or mirrors should be made. Because the size of this project is already quite extensive, additional research and setup building is not done.

The optimization of sensitivity of the receiver cell can be relatively easy done by decreasing the cell volume. However, the use of very small volumes and high pressures creates problems with mismatching acoustical impedance. Due to time limits, this problem is not tackled in the research. Another problem in the use of a smaller volume is that it is more difficult to exactly focus the light beam on the absorber cell. For a stationary setup this will not be problem, but for the demonstration model it should be possible to use a hand-held receiver.

From the research results can be concluded that it is not possible to build a working demonstration setup with the current performance of both parts. It should be possible when additional research is done in optimizing, although this does not fit within the scope of the research. To finish the build of the demonstration setup, another approach should be chosen. There are two possibilities:

1. Use an electronic receiver (photodiode) in combination with the mechanical modulation. In this way basically the setup of Bell is reconstructed and the focus is on modulation techniques.
2. Use the photo acoustic receiver in combination with direct electronic light source modulation. In this way Kleinman's setup is reconstructed and the focus is on demonstrating the photoacoustic effect.

Because the main target of the project was to build a demonstration device for the photoacoustic effect, the second option is chosen and electronic light modulations should be designed.

4.2 POWER LED BASED LIGHT MODULATION

Modern LED technology has developed into a competitive lighting technique with a high light output. In contrast to traditional light bulbs, LEDs use semiconductor technology that directly emits light when a current is applied. This enables LEDs to be modulated up to very high frequencies (>100 kHz). This paragraph will shortly introduce the LED, the modulation setup and the construction.

4.2.1 LED RESPONSE

The used LED light source is a LedEngin 5 Watt - warm white. This LED has a nominal output of 150 lumen at 1000 mA. This is roughly comparable to 250 mW of nominal optical power. A LED is a semiconductor that produces light proportional to the amount of current that is sent through the LED. For optimal modulation of the led output, the current should be modulated between 0 and 1500 mA, with a DC component of 750 mA.

4.2.2 ELECTRONIC LED MODULATION

Because the optical output of a LED is positive current driven and the electronic audio source is AC voltage driven, the electronic circuit has to have five functions to convert this signal.

1. Convert voltage into current
2. Provide a DC offset to let the LED burn at the equilibrium position of 50% intensity
3. Make a variable input amplification to match audio input signal to the LED modulation range
4. Apply a high-pass filter, to protect LED from burning out by low frequency peaks and correct for the frequency response of the receiver
5. Sum the AC and DC signal

To achieve this, the circuit in figure 28 is built.

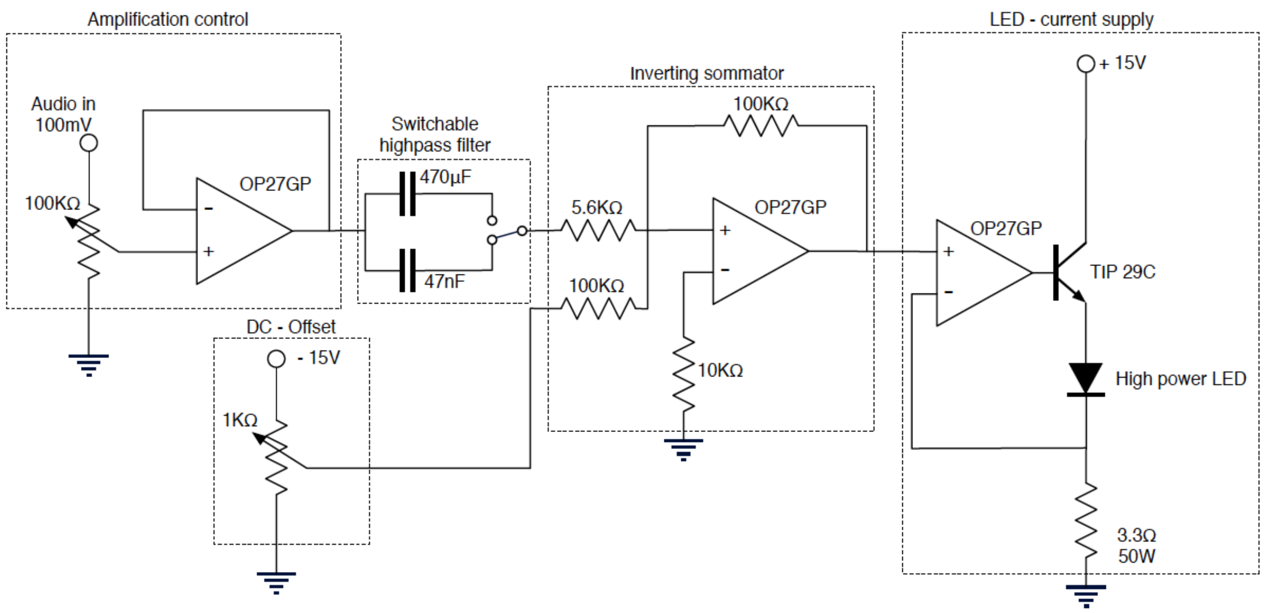


Figure 28 - Electronic modulation circuit

The circuit functions quite straightforward:

- The current supply compares the input voltage with the voltage over the resistor and adjusts current to match these. If 3.3 volt is set on the input, the same voltage is set over the resistor. This equals 1000 mA of current through the resistor and also through the led.
- The DC offset is created by a potentiometer that creates a voltage divider
- The variable amplifying part is done with a potentiometer in combination with an opamp
- The high-pass filter is created with a capacity, switchable between two values, and a resistor
- The combination of AC and DC signal is done with an amplifying summator. The ratio between the resistor before and over the opamp determines the amplifying ratio.

To establish a 750 mA constant current, 2.5 volt should be set over the large resistor by the DC offset (0.75 A * 3.3 Ohm = 2.5 Volt). The AC input signal should modulate this between 0 and 5 volt to achieve 0 to 1500 mA current. Because a typical audio signal has a peak amplitude of around 100 to 200 mV, this should be amplified to 2.5 volt. To do this an amplification ratio of 17.9 is chosen (defined by 100K/5.6K resistor ratio).

The values for the high-pass filter capacity are chosen experimentally. The large 470µF capacitor is chosen to pass-through the low frequencies. With this capacitor low frequencies are clearly audible, but speech is not very good audible and signal gets out of modulation range on low amplifications. The small 47nF capacitor is chosen to remove the low frequencies, which makes higher amplification possible. This makes speech much better audible. The total circuit is built as shown in the picture of figure 29.

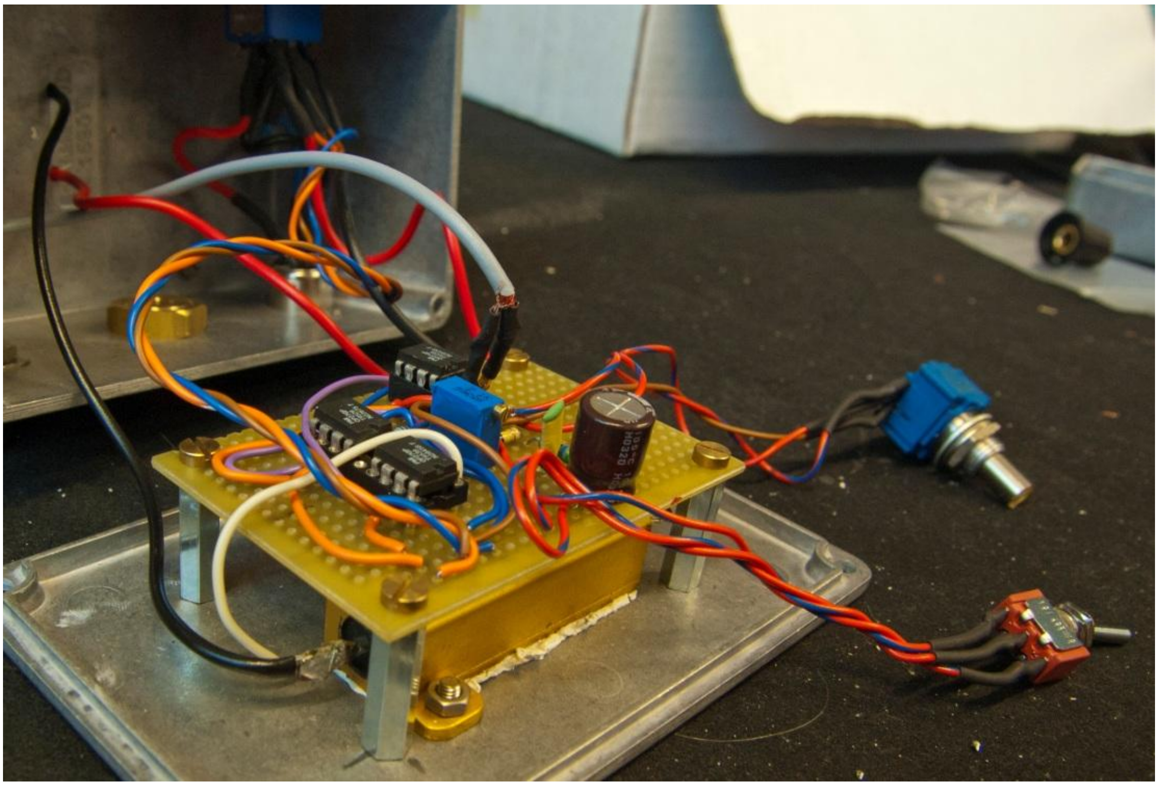


Figure 29 – Electronic modulation circuit print

4.3 IMPROVED ABSORPTION CELL SENSITIVITY

For the demonstration model, the receiver design is slightly improved according to the research results. Three changes are made from the original design:

1. The microphone is replaced by the hearing tubes from a stethoscope, so no electrical parts are used in the receiver and the sound can be made directly audible.
2. The absorption cell is made smaller to create higher pressure differences. To avoid problems with impedances, the diameter is kept the same as the inner diameter of the hearing tube.
3. A parabolic mirror is used to focus light on the absorption cell, in order to absorb more light and make optical alignment less critical than direct illumination.

The absorbing material is still the charred cotton and is distributed uniformly over the cell. A picture of the setup is showed in figure 30.

Figure 30 – Photoacoustic receiver

No additional measurements are done on frequency response or other characteristics of the improved receiver. However, from subjective measurements can be concluded that speech and music is much better audible than on the original setup. The improvements seem to be successful.

4.4 DEMONSTRATION SETUP OVERVIEW

The demonstration setup is built as shown in figure 31. The electronic circuit is mounted inside the aluminum box and placed on a photo camera tripod. Next to the tripod mount are the connections for the power supply (DIN5) and input signal (BNC). A cable adapter from BNC to 3.5mm jack is made to make the setup easy connectable to a laptop, mobile phone or other audio source. Also a function generator can be used to provide the input signal, but maximum signal amplitude of 250 mV should be used to prevent clipping of the signal. On the top are two switches (on/off and the filter switch) and the volume control.

At the back a large heat sink is mounted to dissipate the roughly 15 watts of heat generated by the resistor, transistor and LED. At the front the LED is mounted and a large condenser lens to create the light beam. The whole setup can be transported in a custom made case with foam. In appendix 3 a complete list of all components can be found.

Figure 31 – Demonstration setup

5. Discussion, Recommendations & Conclusion

5.1 Discussion

5.1.1 Absorption cell

The absorption cell research tried to split the photoacoustic phenomena in four separate parts, but it is difficult to see all parts as independent factors. For instance, the frequency response is highly dependent on the absorber cell volume (due to thermal conduction to the cell wall). Also the unexplained deviation of the light intensity response (and the differences between this and Kleinman's research), will influence both volume response as frequency response. These interactions make the actual thermodynamic system a lot more complex than this report presented. Furthermore, the theory assumes both absorber and air to have a fixed position. But due to temperature and pressure differences, the air does move through the absorber cell. For higher light intensities and larger volumes, this could have a significant influence on convective conduction. For small volumes this effect may be neglectable.

5.1.2 Light modulation

The modulation part of the research showed two significantly different systems responses, one mass based and one spring based. From these two setups, it should be possible to design a system with linear modulation depth and a resonance frequency above 2 kHz. A well designed system can even use the resonance frequency of the modulation system to compensate for the frequency response of the absorber cell.

The modulation part of this project was performed less detailed than the absorption cell part, because already halfway the project it became clear that it was not possible to match absorber sensitivity and modulation depth within reasonable time limits. Because the main focus of the project is the photoacoustic effect, the modulation part introduces only the possibilities and difficulties in building a mechanical modulator. No profound research is done to build an optimized mechanical modulator.

5.1.3 Demonstration setup

The design of the demonstration setup showed that (using the research results) it is possible to create a quite straightforward setup that performs well. The subjective measurement that audibility improved from weak to clearly audible, confirms that optimizations have worked.

5.2 Recommendations

5.2.1 Absorber cell

- It is unlikely that the charred cotton produced from a random cotton material is the best possible absorber material. Making use of modern technologies and material science it should be possible to optimize the thermodynamic properties of the material and increase signal.
- As Kleinman's research showed, the use of an acoustic horn and a small absorber cell can significantly increase sensitivity of the absorber cell. Calculating and optimizing acoustical properties of an absorber cell with horn should significantly increase the signal.
- A more complex model of the thermodynamics (including for instance movement of air) should supply an explanation for the measurement deviations. This can be used for minimizing deviations from the theoretical model and increase signal.

5.2.2 Light modulation

- Assuming the vibrating knife setup is the superior technique, material research should be done to build a lightweight and heat resistant optical knife.
- When focal point diameter is known, simulations could be done to optimize amplitude, resonance frequency and spring constant of the membrane system.
- Experiments could be done to use the resonance peak of the combination of membrane and optical knife to compensate for the frequency response of the absorber.
- An acoustic horn could be used to increase pressure difference (and therefore force) on the membrane.

5.2.3 Demonstration setup

- Besides the use as demonstration setup, the photophone can be used for educational purposes. A practicum assignment (i.e. measurements on different absorbers) can be developed to introduce students in the possibilities of photoacoustics.

5.3 CONCLUSION

The research provided a broad overview of the physics involved in the build of a photophone. In both research parts the theoretical analysis was somewhat simplified, according to the deviations in measurement results. However, the theoretical framework proved to be sufficient to predict the majority of the measurements.

The assignment to create a demonstration device for the photoacoustic effect is successfully performed. However, one has to keep in mind that the setup does not demonstrate the actual photoacoustic effect (the expansion of the absorber itself), but the thermal waves in the surrounding air. The built of a mechanical modulator proved to be one bridge too far for the available timespan. Although, no physical limitations were found that prove mechanical modulation to be impossible.

The setup that Bell had in mind 130 years ago but didn't work, was proven to be technically feasible with nowadays knowledge. The research provided an extensive fundament to continue research and finally build the mechanical photophone. This would be a noble job to perform, because it will conclude decades of research and finish the job started by one of world's most respected scientists.

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APPENDICES

APPENDIX 1 - HEAT PROFILE SIMULATION MATLAB SCRIPT

The heat dissipation simulations are done with a simple MATLAB script which uses the finite element method to do numerical calculations on the one-dimensional heat equation (7).

$$\frac{\partial T}{\partial t} - \alpha \frac{\partial^2 T}{\partial x^2} = 0 \tag{7}$$

The script defines an array of 50 elements. The first element absorbs the heat from the light beam and the last element is set at constant temperature because it is in contact with the cell wall. The script performs two steps on each iteration. First the temperature differences between the elements are calculated and multiplied by the heat dissipation coefficient α to calculate the heat flux between the elements. Next the new temperatures are calculated by adding or subtracting the heat flux to the neighboring elements.

The final step is creating a plot from the simulation data in the *temp* array. A heat profile is plotted after every 3000 simulation steps.

```
clear all


length = 50;                        % Define number of elements
ampl = 10;                          % Define amplitude of input signal
diff = 0.3;                         % Define heat diffusion
t = 50000;                          % # of iterations


for freq = [200, 800, 3200, 6400]   %Simulation frequencies

temp = zeros(t,length);             % Create/reset temperature array
flux = zeros(1,length);             % Create/reset flux array
signal = zeros(1,t);                % Create/reset signal array

    % Simulation iterations
    for step=1:t
    time = step/t;
    signal(1,step) = -ampl*sin(time*freq);       % Define input signal

        % Step 1 - Calculate heat flux between elements
        for n=1:(length-1)
        flux(1,n) = diff*(temp(step,n) - temp(step,n+1)) ;
        end

        % Step 2a - Calculate new temperature of first and last element
    temp(step+1,1) = temp(step,1) + signal(1,step) - diff*flux(1,1);
    temp(step+1,length) = 0;

        % Step 2b - Calculate new temperature of other elements
        for n=2:(length-1)
        temp(step+1,n) = temp(step,n) + flux(1,n-1) - flux(1,n);
        end

    end


figure  % Plot figure of multiple heat profiles
hold on
    for n=2000:3000:50000
        plot(1:length,temp(n,1:length))
        XLABEL('Depth (arb. unit)')
        YLABEL('Temperature (arb. unit)')
    end

end
```

Appendix 2 – Measurement microphone diagram

The used microphone in all photoacoustic measurements of chapter two is a simple electret microphone. The brand or type is unknown, but they are produced by several manufactures at shops like Farnell. Typical frequency response of these microphones is flat within 3 dB between 100 Hz and 10 kHz. This is assumed to be good enough for the performed measurements.

This type of microphone needs a power source to produce an electrical signal. The microphone is wired as shown in figure 32.

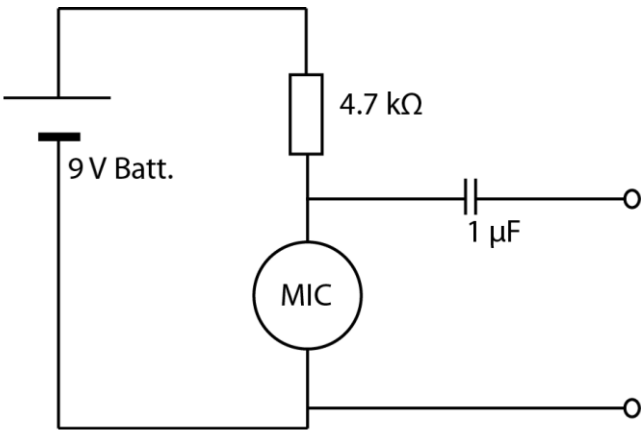

Figure 32 – Wiring diagram microphone

APPENDIX 3 – LIST OF COMPONENTS FOR DEMONSTRATION SETUP

For the construction of the demonstration model a lot of specific components are used. This appendix gives an overview of all the used parts. With this list it is possible to build a copy of the demonstration model.

THE PHOTOACOUSTIC RECEIVER

- Hearing tubes from a stethoscope, no specific type or needs.
- A large parabolic reflector from a *PAR 56* spot (180 mm diameter), used in theaters and other professional lighting applications. Available in online shops or the local sound and light rental shop.
- A cylindrical piece of PVC, to attach the hearing tubes to the parabolic mirror. Piece is custom made in the workshop on the university.
- A glass tube (50 mm length, 4 mm diameter). Has to fit tightly in the inner diameter of the hearing tubes, to ensure air-tight sound transmission. Produced at the glass workshop of the university.
- Charred cotton, produced by heating cotton (from old clothing) to around 300 degrees for roughly 10 minutes in a low oxygen environment. Production methods are easily found on the internet, by searching on '*charred cotton'*.

THE LIGHT MODULATION SETUP

- Electronic circuit:
    - Op-Amp OP27GP (3x)
    - NPN Power Transistor TIP29C (1x)
    - Capacitors: 470 µF (1x) and 47 nF (1x)
    - Resistors: 100 kΩ (2x), 5.6 kΩ (1x), 10 kΩ (1x) and 3.3 Ω, 50 W (1x)
    - Potentiometer: 100 kΩ (1x) and 1 kΩ (1x)
- The LED: LedEngin LZ1-10WW00 (5 Watt - warm white)
- Power supply: XP Power – PCM50UD08
    - Sym. +/- 15 Volt DC power supply, max current +15 V is 2 A, -15 V is 1 A
- Casing:
    - Aluminum case (uncoated for optimal heat transfer)
    - Tripod mount (fabricated at university workshop)
    - Large heat sink for dissipating heat from resistor and transistor
- Connectors and switches
    - Power in: DIN 5
    - Signal in: BNC
    - Filter switch: One-pole, no special requirements
    - Power switch: Three-pole, capable of switching 2 A
- Lens: Condenser lens from old slide projector.
    - Specifications unknown, but every large condenser lens will do
- Lens mount:
    - Thorlabs – LCP03 – Blank cage plate
        - Exact fitting for lens cut out in university workshop
    - Thorlabs – ER2 – Extension rods for adjusting lens position
- Tripod, no special requirements
- BNC to 3.5 mm jack plug adaptor cable, for connecting laptop to setup