

Estimating depth of layered structure based on multispectral speckle correlation

Takahiro Matsumura
Osaka University
Osaka, Japan

matsumura@am.sanken.osaka-u.ac.jp

Yasuhiro Mukaigawa
Nara Institute of Science and Technology
Nara, Japan

mukaigawa@is.naist.jp

Yasushi Yagi
Osaka University
Osaka, Japan

yagi@am.sanken.osaka-u.ac.jp

Abstract

Some objects have layered structures in which a dynamic region is covered by a static layer. In this paper, we propose a new experiment for estimating the depth of the dynamic region using speckle analysis. The speckle is caused by the mutual interference of a coherence laser. We use two characteristics of the speckle. One is the temporal stability of the speckle pattern and the other is the wavelength dependency of the transmittance of the laser. We estimate the depth by computing correlations of speckle patterns using multispectral lasers. Experimental results using a simulated skin show that multispectral speckle correlation can be used for analyzing a layered structure.

1. Introduction

For most objects, light is not only reflected by the surface, but also penetrates it. Recently, studies have externally analyzed the interior of objects using this property. Because it is a safe source without the risk of radiation exposure, there are a variety of analysis application fields using near-infrared light and visible light[1][2]. In many objects, the interior has a layered structure. For example, sweat glands and sebaceous glands exist as the outermost layer, while capillaries and lymphatic vessels spread in the underlying dermis layer. Additionally, in the case of the stem of a plant, there is a vascular bundle that carries the nutrients and moisture inside the epidermis, endothelium and skin layer. It is believed that analyzing the layer structure non-destructively without cutting an object has applications in various fields.

As one of the optical phenomena, a speckle effect has been studied. The speckle effect is observed as a noisy pattern on the surface when an object is illuminated by a laser. The speckle effect was recognized from the early days

when the laser was first discovered. Initially, the speckle effect was regarded as noise in the imaging and was studied for the purpose of its removal. Subsequently, the nature of the speckle effect became clearer. Research then expanded into optical information processing and optical measurement using the speckle phenomenon[3]. Recently, Shih et al.[4] showed that the speckle effect can be used for detecting small changes in a location because the speckle patterns change drastically even if the motion of the object is slight. Zizka et al.[5] have developed a faster and more accurate motion sensing method using a laser speckle. Additionally, imaging blood flows have been studied using the property that the speckle changes occur only under dynamic movement[6].

In this study, we propose a method for estimating the layer structure of an object based on speckle analysis. We assume that the target object has no external motion but motion occurs in the inner layer. According to the characteristic that speckle light reflected only by a static layer becomes temporarily stable, while speckle light reaching a dynamic region changes significantly, we estimate the depth of the static layer by calculating the correlation of successive images. Additionally, we show that the range of the estimated depth can be extended using multiple laser sources that have different transmission properties.

2. Properties of Speckle

2.1. Interference of laser light

As shown in Fig.1(a) when an object is irradiated with a laser light, a wave field is formed by the light scattered at the surface. Light from the object surface is scattered in different directions by the minute irregularities. The scattered light propagates as a spherical wave and interference of the light occurs at each point in space. The phase of the

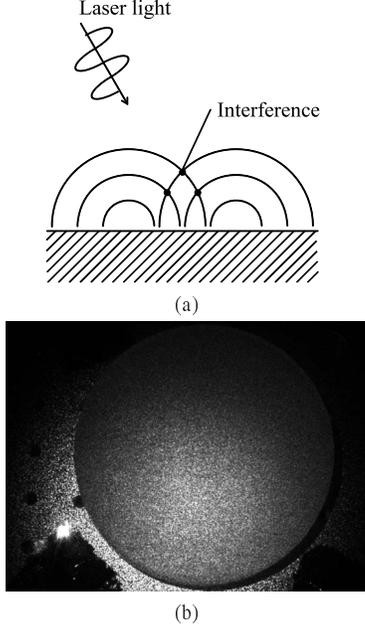


Figure 1: The principle of speckle

light varies depending on the optical path of the scattered light. By the superposition of the light at each point, the wave is destructive or constructive and made light and dark as shown in Fig.1(b). We call this pattern the “speckle pattern”.

2.2. Stability of speckle

When the light source or the object has a slight motion, the optical path of the object changes. Therefore, the speckle pattern changes radically. Conversely, when they are both still, the pattern is stationary.

Because the speckle pattern is formed by the scattering of light at the fine irregularities of the object’s surface, it changes considerably when there is a slight change in the positional relationship between the rough surface and the light. Moreover, the modeling of the speckle pattern is difficult because the additive characteristic of light does not hold. In contrast, when the source and object scene is static, the speckle pattern is stationary. Therefore, observing the speckle pattern enables the detection of dynamic changes in the scene.

3. Proposed method

3.1. Layered structure

Plant stems and human skin have layered structures. In the case of human skin, there is an outer layer in which blood flow does not occur, while there is a dermal layer that has spreading capillaries beneath it. Additionally, plant

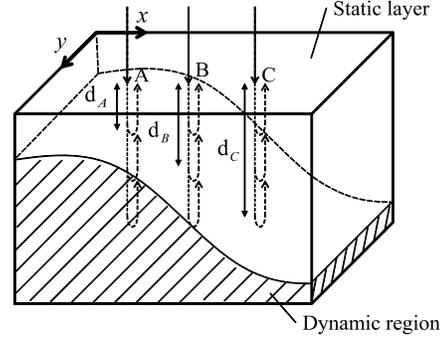


Figure 2: 2D distribution of depth of static layer

stems perform in the same way. There is a skin layer with no movement on the outside, while a layer with a flow of water in the vascular bundle spreads on the inside. The structure of these objects can be regarded as a layered structure, which has a dynamic region under a thin static layer.

This study intends to estimate the depth of the static layer and target the dynamic region existing under it as shown in Fig.2. When the irradiation is only from one direction of the light source, the object surface is spread two-dimensionally. Therefore, at each point in the xy plane, the problem of determining the depth of the static layer at all the sites becomes a problem of estimating the depth $d(x, y)$.

3.2. Light transmittance

Figure 2 shows the state of the optical path to the inside of the object’s surface when it is irradiated at points A, B and C. d_A, d_B and d_C respectively define the depth of the static layer at points A, B and C. When comparing points A, B and C, because more light penetrates the dynamic region at point A than at B, larger speckle changes can be observed with a corresponding increase in the amount of time-varying light. Furthermore, because the light does not reach the dynamic region at point C, speckle changes do not occur and it is stable.

3.3. Speckle correlation

As described in the previous section, the variation in the speckle pattern differs as a function of the depth of the static layer. To numerically evaluate this variation, we adopt the correlation between time-varying speckle patterns. First, with an object irradiated by laser light, we photographed two images continuously. We then obtained a correlation value for the window that is acquired for each pixel of the two images. To calculate the correlation value when the $n \times n$ square window is centered on the pixel x , we consider one vector $i \in \mathbb{R}^p$ as having $p = n^2$ values with a focus on pixel x . We calculate the correlation value $C(x)$ of the i_1, i_2 vector in the pixel that is common to the two

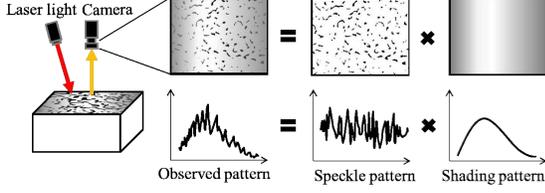


Figure 3: The principle of generating observed patterns

images.

Because the amount of speckle change decreases as the depth of the static layer increases, the correlation value of the two images increases accordingly. Therefore, it can be said that the speckle correlation value and the depth of the static layer have a monotonically increasing relationship.

3.4. Modeling of speckle correlation

In this section, we model the relationship of the speckle correlation value to the depth of the static layer. The observed images contain high frequency speckle patterns, and the low frequency components are similar to each other. In this setting, as shown in Fig.3, the pattern observed is expressed as a multiplication of the speckle pattern, which has an average 1 and shading pattern[7]. That is, assuming that \mathbf{S} is a shading pattern under normal illumination and $\mathbf{r}(x)$ is a speckle component whose average is 0, the observed pattern $\mathbf{i}(x)$ can be modeled as:

$$\mathbf{i} = \mathbf{S}(\mathbf{1} + \mathbf{r}) \quad (1)$$

where $\mathbf{1} = [111\dots 1]^T$. We then consider the elements that make up the speckle pattern \mathbf{r} . When the laser irradiates the object, assuming that d is the depth of the static layer, according to the law of Lambert-Beer[8], the intensity of the light decreases exponentially with the distance ($2d$ round-trip distance) through the object. Assuming that σ is the absorption coefficient and ρ is the reflectance of the object, the attenuation factor α ($0 < \alpha \leq 1$) of the intensity of the laser light reaching the dynamic region is expressed as:

$$\alpha = \exp(-2d\sigma) \quad (2)$$

Assuming that the luminance value vector $\mathbf{r}(x)$ of a small region around the pixel x is the summation of the components $\mathbf{r}_T(x)$ reflected from the object's surface, $\mathbf{r}_S(x)$ reflected only by the static layer and $\mathbf{r}_D(x)$ reflected from the dynamic region can be expressed as:

$$\mathbf{r}(x) = \mathbf{r}_T(x) + (1 - \alpha)\mathbf{r}_S(x) + \alpha\mathbf{r}_D(x) \quad (3)$$

using the attenuation factor α .

It is assumed that $\mathbf{r}_1(x)$, $\mathbf{r}_2(x)$, define the luminance value vector of the two consecutive images. Because the

speckles created by the light reflected only from the object's surface and static layer do not change, then $\mathbf{r}_T(x)$, $\mathbf{r}_S(x)$ is constant. Conversely, because the components reaching the dynamic region change, these are defined as $\mathbf{r}_{D_1}(x)$, and $\mathbf{r}_{D_2}(x)$. Therefore, we can express each $\mathbf{r}_1(x)$ and $\mathbf{r}_2(x)$ as:

$$\mathbf{r}_1(x) = \mathbf{r}_T(x) + (1 - \alpha)\mathbf{r}_S(x) + \alpha\mathbf{r}_{D_1}(x) \quad (4)$$

$$\mathbf{r}_2(x) = \mathbf{r}_T(x) + (1 - \alpha)\mathbf{r}_S(x) + \alpha\mathbf{r}_{D_2}(x) \quad (5)$$

The correlation value $C(x)$ of the two vectors using variance parameters v_T, v_S, v_{12} can be expressed as:

$$C(x) = \frac{\mathbf{r}_1(x) \cdot \mathbf{r}_2(x)}{|\mathbf{r}_1(x)| |\mathbf{r}_2(x)|} = \frac{v_T + (1 - \alpha)v_S}{v_{12}} \quad (6)$$

where

$$v_T = \mathbf{r}_T(x) \cdot \mathbf{r}_T(x),$$

$$v_S = \mathbf{r}_S(x) \cdot \mathbf{r}_S(x),$$

$$v_{12} = |\mathbf{r}_1(x)| |\mathbf{r}_2(x)|.$$

Here, v_T, v_S mean the variance of $\mathbf{r}_T(x), \mathbf{r}_S(x)$, and v_{12} can be expressed by the product of the standard deviations of $\mathbf{r}_1(x)$ and $\mathbf{r}_2(x)$. These parameters are then assumed to be constant irrespective of the pixel. From Equation(2), because the attenuation factor α is a function of the depth of the static layer, the relationship between the depth of the static layer and the correlation value is obtained from Equation(6). If we can measure the speckle correlation value of the object whose depth is known in advance, it is possible to estimate the parameters v_T, v_S , and v_{12} by fitting the measured values to the model Equation(6). Therefore, by modeling the relationship between the speckle correlation value and the depth of the static layer d beforehand, we can estimate, in practice, the depth of the static layer at all the sites from the calculated correlation values.

4. Extension to multiple wavelengths

4.1. Difference between wavelengths

In the previous section, we showed the principle of estimating the depth of the static layer by using the measured speckle correlation values. This is because the depth of the static layer contributes to the variation in speckle resulting from light transmittance.

However, this transmittance changes not only as a function of the material, but also as a function of wavelength. Therefore, when using only a light source of one wavelength, the estimate of the depth of the static layer can be difficult. For example, in the case shown in the left of Fig.4, the light with a wavelength of λ_1 does not reach the dynamic region and there is no change in the speckle pattern. However, for the light with a wavelength of λ_3 , the depth

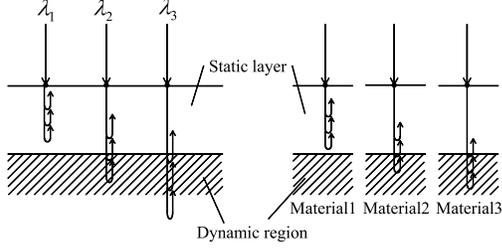


Figure 4: differences of transmittance by wavelengths and materials

reached is too deep, and the speckle pattern changes generally for any depth. In such a case, it is not possible to estimate the depth of the static layer. Moreover, in the example on the right of Fig.4, because most of the light reaches the dynamic region, or may not reach the dynamic region of the object for material 3 and material 1, we cannot estimate the depth.

4.2. Multispectral speckle correlation

To solve the problem in the previous section, in this study, we extended the speckle correlation method to a multispectral approach. Using a multispectral laser, it is possible to reduce the restrictions on the material for which the estimation is difficult when using a single wavelength.

The principle of estimating the depth of the static layer is the same as for a single wavelength. But as shown in Fig.5, by extending to a multispectral laser, the relationship between the speckle correlation value and the depth of the static layer that are different for each wavelength, can be obtained. We define $C_{\lambda_i}(d)$ as the speckle correlation value at a certain wavelength λ_i . Using k types of wavelength, because the relationship between speckle correlation value and the depth of the static layer are also k types, we can express it by the following expression:

$$\mathbf{C}(d) = (C_{\lambda_1}(d), C_{\lambda_2}(d), \dots, C_{\lambda_k}(d)) \quad (7)$$

If \mathbf{C}' is the correlation values that were actually measured, estimated depth d is determined as

$$d = \arg \min_d \|\mathbf{C}(d) - \mathbf{C}'\| \quad (8)$$

5. Experiments

5.1. Setup

First, we performed experiments that mapped the relationship between the speckle correlation value and the depth of the static layer, in advance. The true value of the depth is known from numerical evaluation. We used a simulated

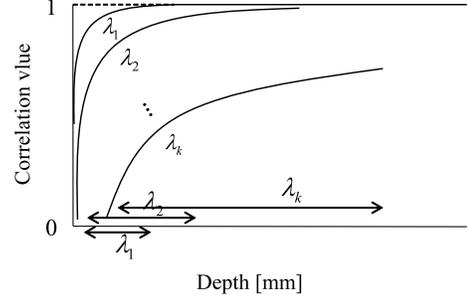


Figure 5: The relationship between the depth of the static layer and the correlation value for each wavelength

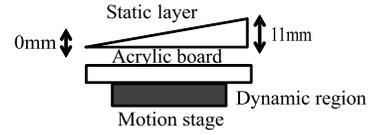


Figure 6: Simulated skin using polypropylene

skin consisting of the dynamic region and the static layer that mimics the skin as shown in Fig.6.

This simulated skin is composed of:

- (a) Polypropylene disk in a static state
- (b) Acrylic plate of transparent color
- (c) Polypropylene disk of motion state

(a) simulates the static layer in the skin, and by varying the depth from 0[mm] to 11[mm] measures the speckle changes at different depths. (c) is to reproduce the dynamic region using a translation stage that can be controlled by a PC. (b) is used for physical blocking so that (a) does not move as a result of the motion of (c). The environment for this experiment is shown in Fig.7. The camera captures speckle patterns by irradiating the above sample with a laser.

5.2. Depth estimation using three wavelengths

In this experiment, we calculated the correlation value of the speckle pattern generated by the irradiation of lasers of 670[nm] in the visible region and 782[nm], 850[nm] in the near infrared region, using the following procedure.

1. In the first picture without any movement.
2. After a small movement, take the second picture.
3. From the two images, calculate the speckle correlation value at each pixel.

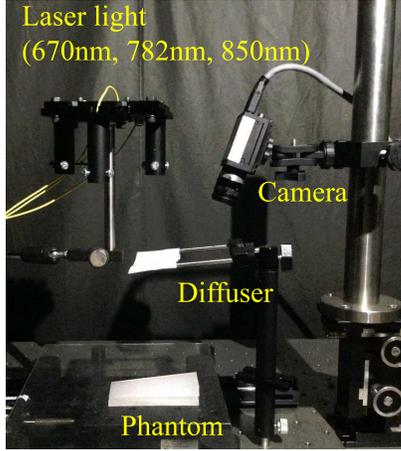


Figure 7: Experiments

Table 1: Parameters of each graph

wavelength	σ	v_T	v_S	v_{12}
670 nm	0.08	0.08	0.86	0.94
782 nm	0.05	0.01	0.87	0.99
850 nm	0.06	0.01	0.65	0.99

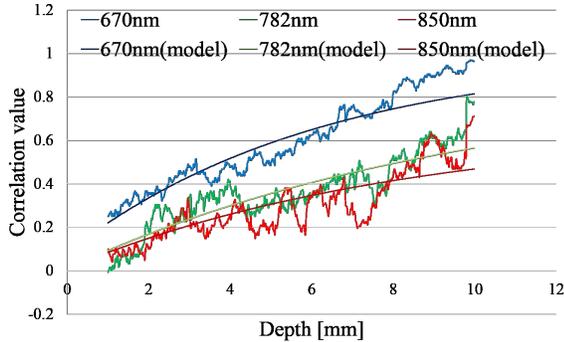


Figure 8: The model-fitting result for each wavelength

We show the relationship between the depth of the static layer and the actual speckle correlation values in Fig.8. Further, by fitting the measured value to the model equation (6), parameters such as shown in Table 1 were obtained. In Fig.8, we show the results of model fitting for each wavelength. Although some errors can be observed between the model and the measurement results, it can be seen that they approximately coincide with each other.

Next, we performed the estimation of the depth of the static layer of the simulated skin, which was measured separately using this model. Fig.9 shows the results of estimating the depth using only a single wavelength and, as

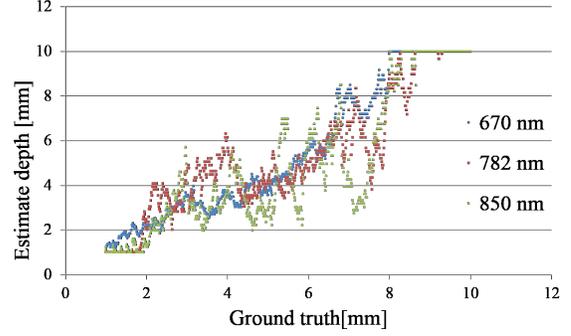


Figure 9: Estimated depths for each wavelength

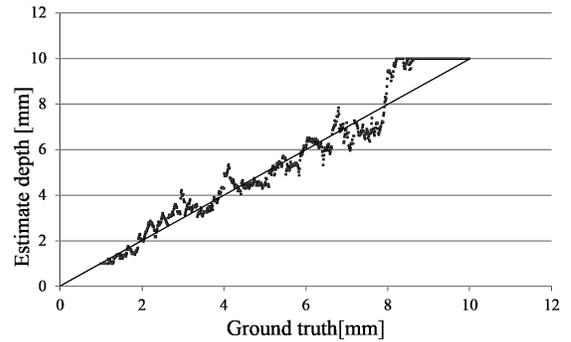


Figure 10: Estimated depths using three wavelengths

shown in Table 2, an error against the true value is listed. It can be seen that the trend in the error varies depending on the wavelength: the error increased suddenly when the estimated depth was more than 7[mm] for the laser of 850[nm]. However, Fig.10 shows the results from estimating the depth where the square sum of the difference between each model is minimized using a three-wavelength laser. Table 2 lists the error against the true value.

The error was less than half the case for a single wavelength, and an accuracy improvement for the estimates was observed by extending to a multi-wavelength laser. From these results, using multispectral lasers, a high correlation was observed in the estimated and actual depths, and effective estimation of the depth of the static layer using the multispectral speckle correlation method proposed in this study, is verified.

6. Applications

As an example of the application of this study, we performed speckle measurements of body tissue. Because of the flow of water and blood within tissue, a dynamic region is always present in the case of living tissue. Therefore, we took additional consecutive shots with the camera and cal-

Table 2: Error between multi and single wavelengths

Wavelength	RMSE [mm]
670 nm	0.8069
782 nm	1.0781
850 nm	1.4675
multiple	0.6276

culated the speckle correlation value. We showed the results of visualizing the speckle correlation values when irradiating human fingertips with a laser in Fig. 11. In this image, it is clear that the correlation value increases as the luminance value changes from blue, to green, to red.

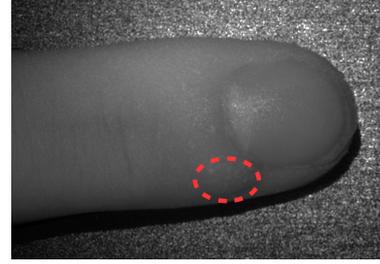
In Fig. 11, the same degree of speckle correlation can be seen for the skin. Although this is slight, it can be seen that speckle correlations for the nails are higher. Therefore, the static layer of the skin area is thin and the dynamic region spreads just below this layer, while for the nail area it can be seen that the static layer is thicker than for the skin. Further, the area surrounded by a dotted line in Fig. 11(a) is calloused skin. Because there was no speckle change in the correlation image, there was no motion such as blood flow in this area and we found that the depth of the dynamic region was not achieved.

This application has limitations. In the experiment using a simulated skin based on polypropylene, we can calibrate the relationship between the correlation and the depth of the dynamic region because the depths are given. However, in body tissue, the depth of the dermis layer is not given. Therefore, we can only perform relative evaluation in the proposed method.

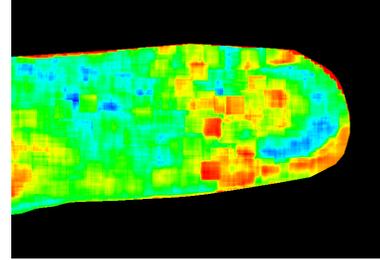
7. Conclusions

In this study, to analyze an object with a layered structure such as biological tissue, we used the speckle pattern generated by a laser. The layered structure has a dynamic region, such as blood flow behind the static layer. We proposed a method for estimating the depth of the static layer from the correlation value of speckle changes using the characteristic of speckle patterns. The characteristic is stable in time relative to a static object. Further, because of the significant limits for the estimated depth using only a certain wavelength, we demonstrated a method for estimating the depth of the static layer over a greater range. Because the transmittance depths of the light inside the object are different depending on the wavelength, extending the light to multi-spectral lasers enabled us to estimate the depth to a greater extent.

We performed the estimation using a simulated skin based on polypropylene. We compared the estimated depth for the static layer with real depth. There was a high cor-



(a) observed image



(b) correlation image

Figure 11: Speckle correlation images of fingertip

relation between the two. Additionally, as applied to living tissue, we measured the state of speckle pattern changes of the fingertip of a human. Appropriate speckle changes were observed in the skin, nail and calloused areas.

In this study, the material subjected to depth estimation was only of one type, namely polypropylene, so in the future we plan to measure the relationship between the correlation value and the depth of the static layer for various materials. Additionally, with application to living tissue, rather than a relative evaluation of the skin, such as that of shallow blood flow under a nail, we plan to measure the depth distribution of more detailed blood flow quantitatively.

References

- [1] Yasunori Ishii, Toshiya Arai, Yasuhiro Mukaigawa, Jun'ichi Tagawa, and Yasushi Yagi. Scattering tomography by monte carlo voting. In *Proc. MVA2013*, 2013. 1
- [2] Kenichiro Tanaka, Yasuhiro Mukaigawa, Yasuyuki Matsushita, and Yasushi Yagi. Descattering of transmissive observation using parallel high-frequency illumination. In *Proc. ICCP2013*, 2013. 1
- [3] Schmitt, Joseph M., S. H. Xiang, and Kin M. Yung. Speckle in optical coherence tomography *Journal of biomedical optics*, 4.1, pp. 95–105, 1999. 1

- [4] Yi Chang Shih, A Davis, SW Hasinoff, F Durand, and WT Freeman. Laser speckle photography for surface tampering detection. In *Proc. CVPR2012*, pp. 33–40. IEEE, 2012. 1
- [5] Jan Zizka, Alex Olwal, and Ramesh Raskar. Specklesense: fast, precise, low-cost and compact motion sensing using laser speckle. In *Proc. ACM symposium on User interface software and technology*, UIST '11, pp. 489–498, 2011. 1
- [6] Guy Satat, Christopher Barsi, Ramesh Raskar. Skin Perfusion Photography. In *Proc. ICCP2014*, 2014. 1
- [7] Eom, Kie B. Speckle noise removal by robust modeling. In *Proc. ICIP2003*, Vol.3, pp.III–165, IEEE, 2003. 3
- [8] A. Beer. Bestimmung der absorption des rothen lichts in farbigen flussigkeiten. *Annalen der Physik und Chemie*, Vol. 86, pp. 78–88, 1852. 3