Karlsruhe Institute of Technology

Physics Laboratory
Invisibility cloak

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1. Introduction

The dream of invisibility was always in the imagination of humankind and, therefore, there is a plenty of literature about the wonders of the invisibly ability. However, this so far dream is now becoming a feasible reality, with physic and engineering techniques.

The light rays that come to our retina is the result of a combination of different interaction between the light with another source of light and/or the light a matter. These interactions lead to us the perception of our surround environment through transduction of this light signals in to electric pulses in our retina. One illustration is the green color of the leaves in the trees, the sun light hits the leaf, that has photosensitive molecule (Chlorophyll A, majoritarily) that absorbs the short wavelength (blue range) and long wavelength (red, infrared range), reflecting the green spectra. To make light bends around or avoid the direct interaction of the incident light over a object is the key factor for invisibility.

The achieve of feasible invisibility cloak using the control of the trajectory of the light in anisotropic media was proposal recently in 2006 (Pendry, 2006). By using the spatial design of the material to mold the path of light around an object, the object in the path of light wouldn't interact with the light, leading to the invisibility. The light path in an anisotropic media can be described as a diffusion equation according to Schittny et al., 2016. Manipulating the spatial properties of the scalar diffusivity it can band the light around a object of interest and, thus, to accomplish the invisibility profile.

In the experiments described in this report we will analyze some fundamental parameters the will lead to a empirical calculation of the diffusivity. In the first approach, we calculated the diffusivity using the ballistic transmission of monochromatic laser through different concentration TiO2 in polydimethylsiloxane solid media (PMDS). In the second approach, we use the diffusive transmittance (Tdiff) to achieve the value of the diffusivity. In addition, carried a extra experiment that was carried out with the purpose to observer the effect of the thickness of the material and the diffusivity. The equations that we used for the investigation were:

$$P(z) = P_0\, e^{-\frac{z}{l_s}} \tag{1}$$

P is the Ballistic transmitted power;
z is the Thickness of the sample;

ls is the scattering mean free path (represents the random path that light describes inside a material; is related to the inverse of the density of scattering centers and scattering cross section)

$$l_t = \frac{l_s}{1-g} \tag{2}$$

g is the anisotropic factor (0,523);

l_t is the transport mean path (represents the average distance that a photon propagates before the direction gets random);

$$D = \frac{1}{3} v \, l_t \tag{3}$$

D is the diffusivity; v is the velocity of light in the material (n=1,4);

$$T = T_0 \frac{1}{2 + \frac{K \cdot z}{D}} \tag{4}$$

T is for diffusive transmittance; K is the escape velocity of a photon;

$$K = \frac{c_0}{2An} \tag{5}$$

A is index constant between air and PDMS (A=2.95), n is the refractive index of the material (n=1,4);

By the end of the experiment, we investigated different invisibility cloak shell under a object inside PMDS solid media.

2. Experimental Set up

a) Ballistic transmission

During the first experiment, the ballistic transmittance of samples with different scattered concentration is measured. With these the corresponding *mean free path* evaluated as well as the diffusivity. The samples consist of a transparent basic material, *polydimethylsiloxane* (PDMS). The diffusivity refers to the scattering particles, *titania* nanoparticles, which are put in to the basic material in different concentrations (0.1, 0.15, 0.2, 0.25, 0.3 mg/cm^3). Every sample has same shape and dimensions with a thickness of 1.5 *cm*.
The experimental set up consist of a laser light source and a photon counter, in which between the sample is placed. The Laser is a pulsed semiconductor laser with wavelength of 638 *nm,* a peak power of 1 *W* pulse time of approx.. 50 *ps.* Since the pure laser intensity can cause damage to the photo detector, neutral density filters are placed directly after the laser the laser source. The transmittance of the filters are 10%, 1% and 0.1%. To maintain in the dynamic range of the detector, the combination of filters used is changed as necessary.
The gathered data allows to calculate the *mean free path* of each sample and hence the diffusivity. This is done by comparing the photon count (corrected with filter factor) of a pure PDSM sample with the photocount of the samples.

b) Diffusive transmission setup and cloaking analysis

In the second set up a LCD monitor is used as a background light source while a camera takes pictures of the illuminated sample. The samples evaluated are the same as in the first set up. With a program, based on LabView. The illuminating area as well as the camera are controlled with a LabView program.
The light shines through the illuminated samples. Taking a picture of the shining sample, gives the opportunity to read out the intensity of each single pixel. After defining a uniform illuminated area in the pictures, the mean Intensity of this defined area over all colours is computed. The operation of pixel analysis is made with *MATLAB*. Analogues to the ballistic transmission, the transmission can be calculated by knowing the brightness and the exposure time of the pictures.
The set up described is also used generating data for analysing the disparities in different invisibility shells.

3. Results

In this section the outcome of the real experiments are presented. All experiments take place in a black box. It is important to avoid any kind of stray light going in to the detectors during the measurement, since the equipment is extremely sensitive to light. Stray light could falsify the result.

a) Ballistic transmission measurement

With the measurement described in the section *2.a) Ballistic transmission* a data set was generated (see *Table 1*). In order to enhance the reliability of the procedure, the photon count is done three times. Each time the sample was slightly deposition, so that the laser beam hit the surface a different part of the surface (middle, right and left). Especially sample 0.2 shows a strong fluctuation for the different positions. The scattering particles are not homogenously distributed over the samples volume.
With the averaged photon count, the filter factor and Equation (1) the mean free path l_s of the samples is determined. Taking also equation (2) and (3) into account, it is then possible to calculate diffusivity D.

Table 1 Results of the ballistic transmission measurement

Concentration [mg/cm³]	Photon count				Filter-factor	l_s [cm]	D 10^5 [m²/s]
	Middle	Right	Left	Average			
0	1.03x10⁴	1.23x10⁴	1.14 x10⁴	1.13x10⁴	10^6	reference	reference
0.1	1.67x10⁵	1.64x10⁴	4.04 x10⁴	2.45x10⁵	10^3	0.391	5.85
0.15	6.18x10⁴	6.35x10⁴	6.50 x10⁴	6.34x10⁴	10^2	0.200	3.00
0.2	5.20x10⁴	8.30x10⁴	1.35 x10⁵	9.00 x10⁴	10^2	0.210	3.14
0.25	3.18x10³	3.63x10³	3.60 x10³	3.47 x10³	10^2	0.144	2.16
0.3	2.59x10³	2.55x10³	2.60 x10³	2.58 x10³	10^2	0.140	2.10

In the plot of D (see *figure 1*) it is noticed that the diffusivity drops by ricing scattering particle concentrations. The decrease of the diffusivity should have the shape of $\ln(x)^{-1}$ according to literature (Schittny et al., 2016). The overall profile can be noticed but due to inappropriate measurement lead to a lack of accuracy. Furthermore, a higher number of samples would lead to a more reliable fit.

Figure 1 Plot of diffusivity according to ballistic transmission

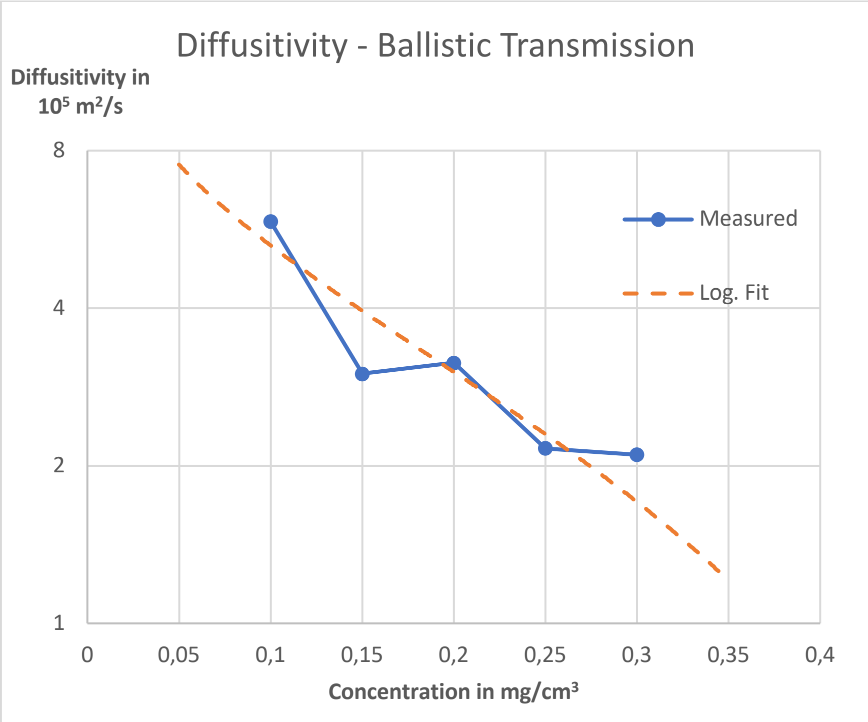

Figure 1 Plot of diffusivity according to ballistic transmission

In addition, it is investigated how the diffusivity relays on the sample's thickness. In order to do so, the measurement described previously is done for combination of up to three samples (thickness still 1.5 *cm*) with same concentration of 0.1 mg/cm^3. The result of this experiment (see *figure 2*) shows the expected decrease of intensity proportional to e^{-x}.

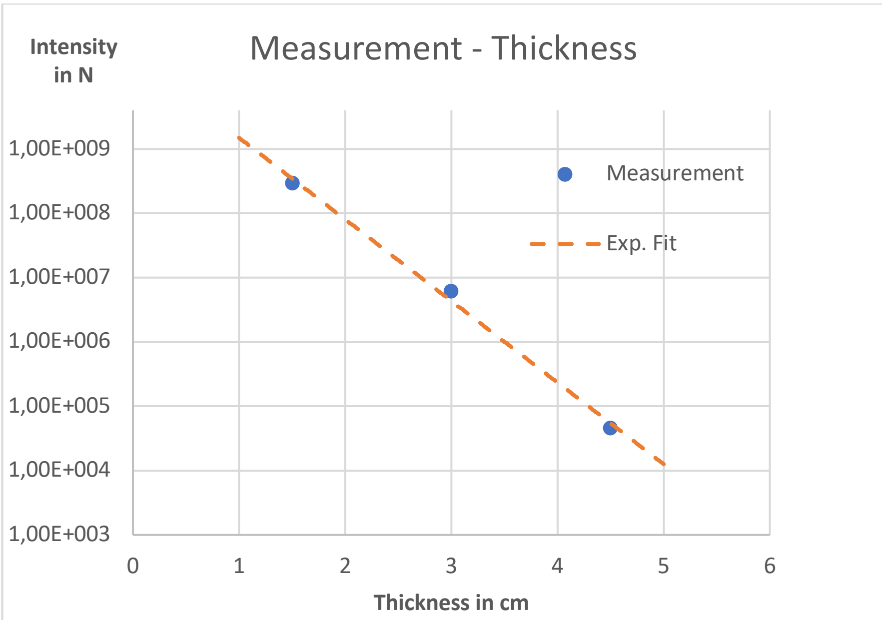

Figure 2 Plot of intensity over different thicknesses

b) Diffusive transmission measurement

With the changed setup, described in section *2.b) Diffusive transmission setup and cloaking analysis,* the diffusivity for the samples was determined in a more adequate way. The brightness of the pictures made is analysed in *MATHLAB*. The intensity is averaged over the three different sensor colours RGB.

The value of intensity refers to the dynamic range of the sensor of 8-bit (see *Table 2*). The calculation of D refers to the equations (4) and (5).

Table 2 Brightness analysed for different samples

Concentration in [mg/cm^3]	Intensity 8-bit	Exposure time	D in 10^5 [m^2/s]
0	223.35	6052	reference
0.1	211.92	22779	2.77
0.15	209.37	30808	1.59
0.2	216.84	31478	1.62
0.25	192.53	37458	1.05
0.3	188.19	38169	0.99

The plot of D (see *figure 3*) also shows the expected profile, similar to experiment a).

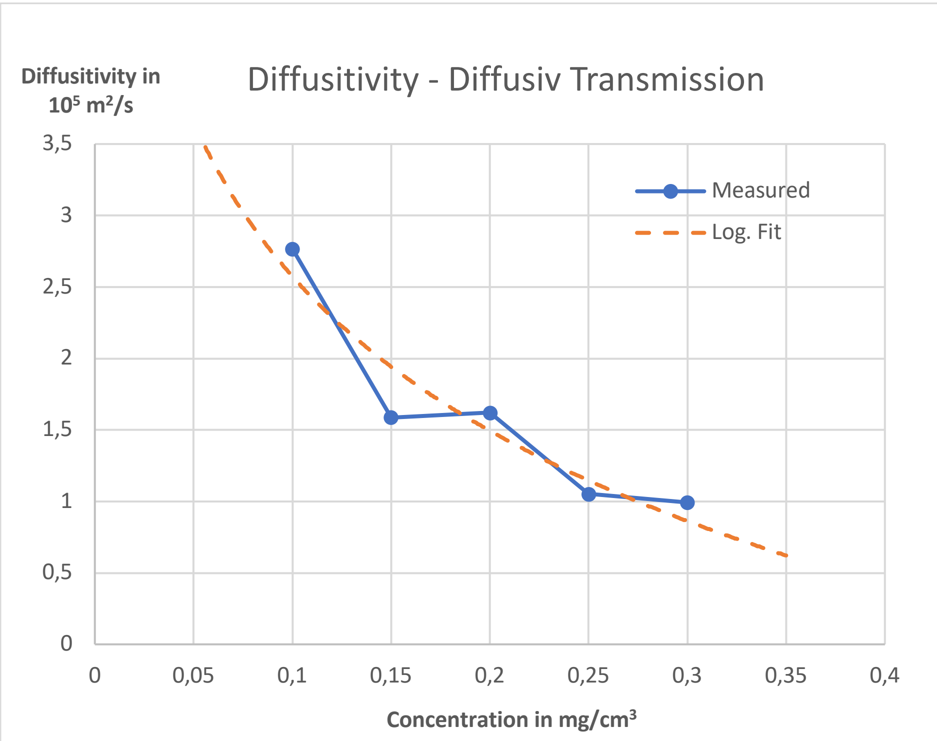

Figure 3 Plot of diffusivity according to diffusive transmission

c) Invisibility cloak

In this experiment the different invisibility shells are evaluated. The Samples, except of the reference one, contain a metal tube positioned vertically in the centre of the rectangular PMDS samples. All samples have the same concentration of scattering particles. The desired invisibility is realized by covering the metal tube in a shell of lower refractive index, compared to PDSM. The differences in the invisibility refers to cloak used.
The shown intensity profiles (see *figure 4 to 8*) are made with *MATLAB*. The profiles give the horizontal intensity distribution, averaged over a homogenous vertical region (see *figure 1*, marked with red lines).

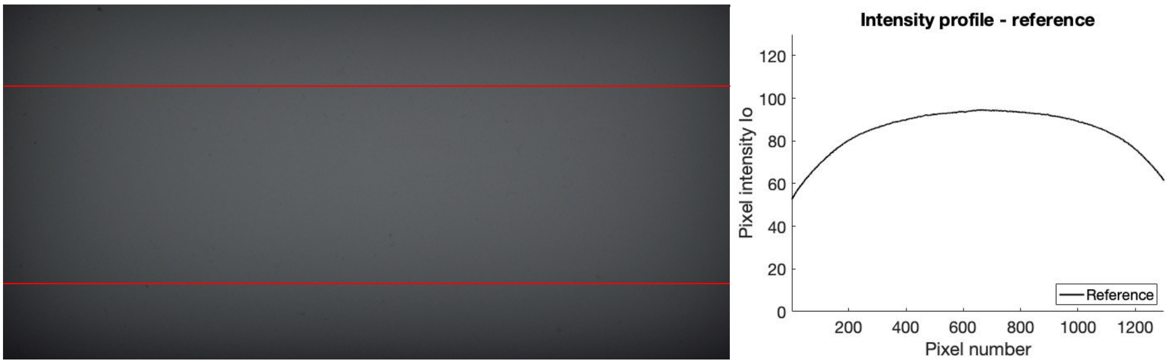

Figure4 Picture and intensity profile sample-reference

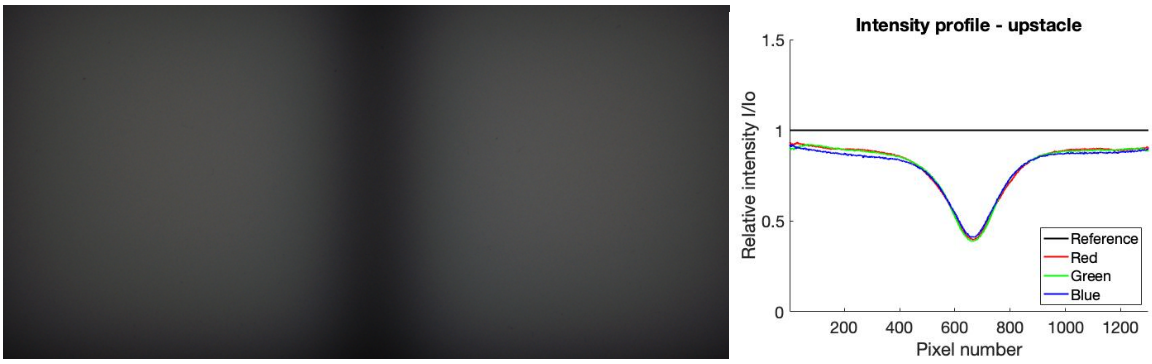

Figure5 Picture and intensity profile sample-obstacle

Figure6 Picture and intensity profile sample-C1

Figure7 Picture and intensity profile sample-C2

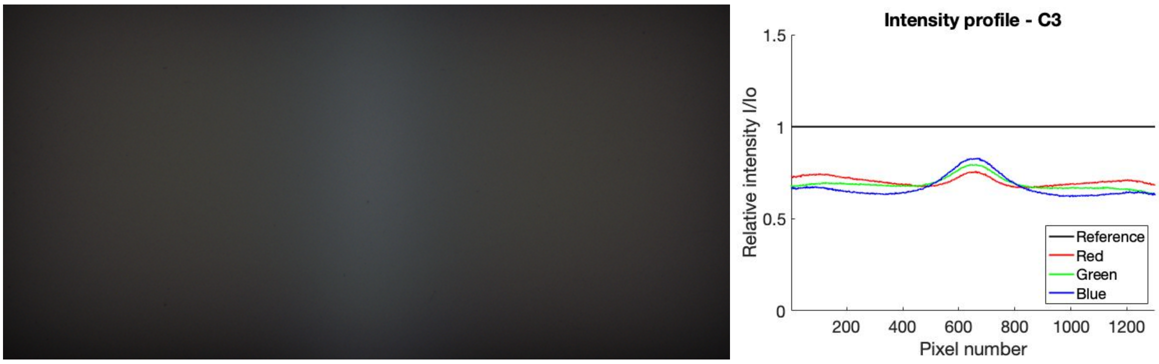

Figure8 Picture and intensity profile sample-C3

4. Conclusion

For the Calculation of the Diffusion coefficient:
Its noticed that the concentration affects the scattering mean free path of the light l_s. As the theoretical equation of l_s suggests. This is due to the fact that the ls is inverse proportional to the density of scattering atoms, in other words the scattering particle concentration (TiO2).
According to the measurements of the ballistic transmitted power and following the mean free path, the diffusivity *D* show some irregularity. This is related to probably a misleading of the experiment. Especially the concentration 0.2 showed inhomogeneity in diffusivity related to position of the incident light.

Regarding the results of the 2nd and the 3rd the overall behaviour of the diffusivity related to the concentrations is the same. The absolute values differ tremendously. This inaccuracy in the measurements be by the following reasons:

- Different light sources concerning the wavelength
- Laser monochromatic (red), LCD display with RGB
- Different measurement set up with different accuracy
- Measuring small point of material (more statistically error possible) vs measuring a bigger area

Analysing the cut-offs (see *figure 4 to 8*) of the different cloaks leads to the following order from 1 to 3 with 1 the most effective cloak to worst one.

1. C1
2. C2
3. C3

The sample C2 shows an intensity drop over the obstacle, this is noticed as a “shadow”, it manages to hide the obstacle better than without cloak. The diffusivity of the shell structure has to be increased to achieve a better result. The overall higher brightness might come from a slightly different diffusivity of the host material.
The sample C3 shows an intensity increase over the obstacle, this is notice as a brightness. This means that the diffusivity of the shell structure is too high and leads too much light into the area of the obstacle.
Sample C1 shows the least intensity deviation in intensity profile. Indeed, the manipulation of the light is observable in the different wavelengths, which results in a slight coulure shift to the blue over cloak. Since short wavelengths has a higher scatters probability compared to longer

ones, this reasons in the slightly bigger intensity in the blue spectra compare to the red and green.

5.Reference

Pendry, J. B. (2006). Controlling Electromagnetic Fields. *Science*, *312*(5781), 1780-1782. doi:10.1126/science.1125907

Schittny, R., Niemeyer, A., Mayer, F., Naber, A., Kadic, M., & Wegener, M. (2016). Invisibility cloaking in light-scattering media. *Laser & Photonics Reviews*, *10*(3), 382-408. doi:10.1002/lpor.201500284