Karlsruhe Institute of Technology

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Cloaced grids on solar cells
(Getarnte Kontakte auf Solarzellen)

Bachelorarbeit
von

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Titelbild

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Bearbeitungszeit: 01.02.2016 – 01.05.2016

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Prof. Dr. Martin Wegener

Contents

1. Introduction

During the last few years, the efficiency of solar cells could be raised significantly through research and development on different aspects of the solar cell. Besides reducing electrical losses and improving the materials used in solar cells (such as the material for the semi-conductor), we can also try to improve optical properties of the solar cell. On the one hand-side, it is important to reduce reflections and on the other hand-side, it is important to guide as much light as possible to the optical active areas. In this Bachelorthesis, we will concentrate on guiding as much light as possible to the optical active areas. One issue concerning this is cloaking the contact fingers and bus-bars on solar cells to guide the light, which would have hit the contact grid on solar cells, to the optical active areas. This can be used to enhance the efficiency of solar cells.

2. General part

2.1. Description of the problem

We want to investigate in the two dimensional design of a surface to get the contact-fingers and the bus-bars cloaked. It is important to cover a as large as possible angular-acceptance as well al a as homogeneous as possible light distribution on the active area of the solar cell. The designs we want to concentrate on are Polymer structures (n=1.5), which should have the right refraction-properties. In this Bachalorthesis, we will not take any reflection into account.

2.2. State of the art

In order to improve the optical properties of solar cells a lot of research has been done. It is important to minimise reflections on the sunny side of the solar cell and in addition to that it is also important to guide as much light as possible to the optical active areas of the solar cell. Reflected light and light that hits the contact grid and the busbar is lost. There are also other approaches of increasing the efficiency of solar cells such as reducing the electrical losses.

The question we want to deal with is how to minimise light that hits the contact grid and the busbar. Before we talk about how we will try this, let us have a look at the most popular approaches to minimise the losses caused by this effect.

You can reach this by decreasing the contact grid and the busbars. This can be done through using back contact solar cells [KB06] or emitter wrap through solar cells [GSB92].

Another approach is to design the sun-side of the solar cell in a way that the light in the end hits the optical active area. In other words, we will try to cloak the busbars and contact fingers.

2.3. Ansatz used in this thesis

In this Bachelorthesis, we will simulate and discuss a optical cloak for cloaking contact fingers and busbars on solar cells. All in all, we want to discuss three different approaches. The first approach is to cover the sun-side of the solar cell with a thin polymer (n=1.5) and design the surface of the polymer in a way that the light coming from all different angles is refracted as uniform as possible to the optical active areas of the solar cell. The surface of the polymer for one dimensional cloaking has already been designed. We will reuse the one dimensional solution proposed in the paper [SWG+15]. The second approach is to design the surface of the polymer similar to a fresnel-linse. This means that the linse is not continuous any more. The surface is divided into pixels and each pixel can be rotated free. This allows a optimal surface for normal incident. In the end, we will design a metasurface to fulfil the optical requirements and compare all three designs.

2.4. Theory

In order to design optical interfaces with specific optical properties, it is important to emphasise the most important physical formulas used for the simulations. In general, on a interface between medium 1 with refractive index n_1 and medium 2 with refractive index n_2, we observe refraction and refraction dependent on the inclination angle and on the two refractive indexes. In addition to that, the intensity of the refraction and reflection is also dependant on this values.

2.4.1. Ordinary refraction and reflection

On the border between medium 1 with refractive index n_1 and medium 2 with refractive index n_2 light doesn't travel on straight lines. Instead, The light gets refracted by Snell's law. ordinary law of refraction: (Snell's law)

$$n_1 \cdot \sin(\alpha) = n_2 \cdot \sin(\beta)$$

ordinary law of reflection:

$$\alpha = \gamma$$

The angle α is the angle between the ray in the medium 1 and the normal vector of the surface defined by the boarder of the two media pointing into medium 1 and the angle β is the angle between the ray in the medium 2 and the normal vector of the surface defined by the boarder of the two media pointing into medium 2. We use Snell's law in vector-form for computations.

2.4.2. Generalised refraction and reflection

On the interface between two materials with different refractive index we can in principle also think of a additional phase the light gets when it hits the interface. This leads to a more generalised law of refraction and reflection. ([YGK$^+$11] and [YC14]) Generalised law of refraction ([YC14]):

$$\begin{aligned} n_2 \cdot \sin(\theta_2) - n_1 \cdot \sin(\theta_1) &= \frac{1}{k_0} \cdot \frac{d\phi}{dx} \\ \cos(\theta_2) \cdot \sin(\phi_2) &= \frac{1}{k_0} \cdot n_2 \frac{d\phi}{dy} \end{aligned}$$

Generalised law of reflection ([YC14]):

$$\begin{aligned} \sin(\theta_2) - \sin(\theta_1) &= \frac{1}{k_0 n_1} \frac{d\phi}{dx} \\ \cos(\theta_2) \cdot \sin(\phi_2) &= \frac{1}{k0 n_2} \frac{d\phi}{dy} \end{aligned}$$

2.5. Simulations

Matlab is used for simulations. The ray-tracer for the three problems are self-written. In order to compare the methods with each other, we introduce the relative improvement. All the calculations of the improvements are done in the same way like [SWG$^+$15].

2.5.1. Investigation into the quality of the design

In order to describe the quality of a given design we need to figure out which quantity is best to measure the quality of the design. The most important parameter is the number of rays hitting the contact grid. Perfect optical cloaking means that the number of rays hitting the contact grid is zero. However, in addition to that, we are also interested in a as homogeneous as possible light distribution on the solar cell. Focusing the light on one spot might lead to an local increase of temperature and therefore to a decrease of efficiency of the solar cell. In order to take the homogeneity into account, we can calculate the average distance from every point the ray hits the solar cell to the perfect design point, which in given by the following one dimensional linear coordinate transformation.

$$x' = \frac{R_2 - R_1}{R_2} \cdot x + R_1$$

2.5.1.1. Relative improvement

The relative improvement tells you how good the optical design works compared to no optical design at all. It is defined as:

$$\xi + 1 = \frac{\text{energy deposited on active area with cloak}}{\text{energy deposited on active area without cloak}}$$

Using this, you can derive the following formula for the relative improvement: (for derivation see supplementary material of [SWG+15])

$$\xi = \frac{N}{N0 \cdot (1 - f)}$$
$$f = 1 - sx \cdot sy$$

ξ describes the relative improvement, sx and sy are the scaling factors in x- and y-direction, N0 is the total number of rays and N is the total number of rays minus the number of rays on contact Grid. The maximal possible improvement becomes: ($N_{max} = N_0$)

$$\xi_{max} = \frac{f}{1 - f}$$

For each inclination angle, we can calculate the relative improvement. However, the relative improvement does not tell so much about the improvement of a solar cell installed for example on a roof. Therefore, we introduce the annual improvement, which is the annual average of the relative improvement.

3. Simulations for continuous surface design

3.1. One dimensional solution using freeform solution

Optical cloaking of contact fingers has already been done in the following paper [SWG$^+$15]. With this technology, it is possible to cloak obstacles in one dimension, which are located between $x = 0$ and $x = R_1$. In the paper [SWG$^+$15], an analytical approximation in order to fulfil the optical properties is derived as well as an numerical solution. The analytical approximation is given in formula 3.1. In this case, y(x) describes the boarder between the polymer (n=1.5) and air (n=1).

$$y(x) = \sqrt{y^2(0) + \frac{R_1}{1 - \frac{1}{n}} \cdot \left(2x - \frac{x^2}{R_2}\right)} \tag{3.1}$$

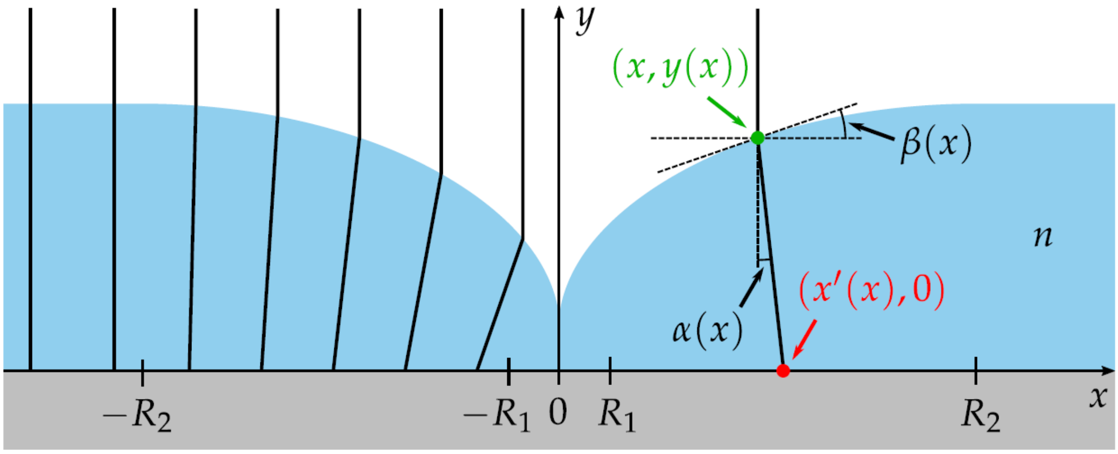


Figure 3.1.: source:[SWG$^+$15][Fig. 2], One dimensional coordinate transformation x $\rightarrow$ x' of a point to a finite interval with width $2R_1$ leading to an angle distribution $\alpha(x)$. This distribution can be realized by a freeform surface y(x) of a dielectic with constant refractive index,n, on top of the solar cell. The local surface inclination angle is denoted by $\beta(x)$

A picture of how the surface looks like can be found in figure 3.1. In order to investigate in the advantages of the freeform solution, the optical cloak has been produced and tested. In one dimension they have shown that " transformed freeform polymer surfaces provide complete remedy of the shadowing problem. Potentially, these structures can be even mass manufactured." ([SWG$^+$15][p. 853])

3.2. Blending of the two one dimensional solutions

Solar cells have on the sun-side two sorts of electrical contacts for collecting and transporting electrons. These are called busbars and contact fingers. The contact fingers and busbars are elongated perpendicular to each other. Usually, the busbars are larger than the contact fingers. From the section 3.1, we know that cloaking in one direction turns out to work well. However, it is evident that a complete cloak of both, the contact fingers and the busbars, would lead to an optimal result. The first approach of the two dimensional problem is to investigate into an analytical solution.

Since it is shown that an analytical approach does not lead to a solution to the problem, we now want to blend the one dimensional solution in order to get a as good as possible solution. Different blendings are for instance:

$$z_1(x,y) = a \cdot f(x) + b \cdot g(y)$$
$$z_2(x,y) = f(x) \cdot g(y)$$

We look at the performance for normal incidence and it turned out that the following solution fits best for normal incidence:

$$z(x,y) = \sqrt{a \cdot f(x)^2 + b \cdot g(y)^2} \tag{3.2}$$

3.3. Simulation rectangular unit cell

Most solar cells nowadays consist o rectangular unit cells. Therefore, we want first have a look at a rectangular unit cell. We chose the proportions of the cell with 1000 units in x direction and 100 units in y-direction. The x-scaling and y-scaling factors are set to be $sx = sy = 0.9$. This means that $1 - sx \cdot sy = 19\%$ of the surface is covered with metal. The contact grid of the solar cell is indicated by the darker areas in figure 3.3. The maximum possible annual improvement is $\xi_{max} = 23.46\%$.

3.3.1. Optimised for normal incidence

As you can see in formula 3.2, the parameters a and b can be chosen freely. In order to optimise the parameters, we first optimise the design for normal incidence. The fitness of a design describes how good a given design performs under chosen fitness- parameters. For fitness measurement for normal incidence, we take the number of rays and the average distance of the point the rays hitting the solar cell and their design point. With optimisation, we mean finding the parameter set for highest fitness of the design.

Table 3.1.: Parameters for simulation for rectangular unit cell (500 x 50 units), optimisation means what constellation has been optimised (normalinc. means optimisation for normal incidence with number of rays on contact grid and average distance to deign point as fitness, annualimpr. means oprimisation for annual improvement using the annual improvement as fitness, only f(x)/g(y) is just the solution being perfect for x or y direction)

a	b	y0x	y0y	rx1	ry1	ξ+1	optimisation	[nalphas,nbetas]
2.07	5.00	49.77	55.54	51.00	9.46	1.1371	annualImpr.	[10,10]
2.07	5.00	49.77	55.54	51.00	9.46	1.1101	annualImpr.	[20,20]
1.9	2.0	75	70	50	5	1.1071	normalinc.	[10,10]
1	0	50	0	50	0	1.1025	only f(x)	[10,10]
0	1	0	5	0	5	1.0789	only g(y)	[10,10]

In order to get a feeling of how the freeform surface for a rectangular surface optimised for normal incident looks like, have a look at figure 3.2. The solar cell sits at $z = 0$ and

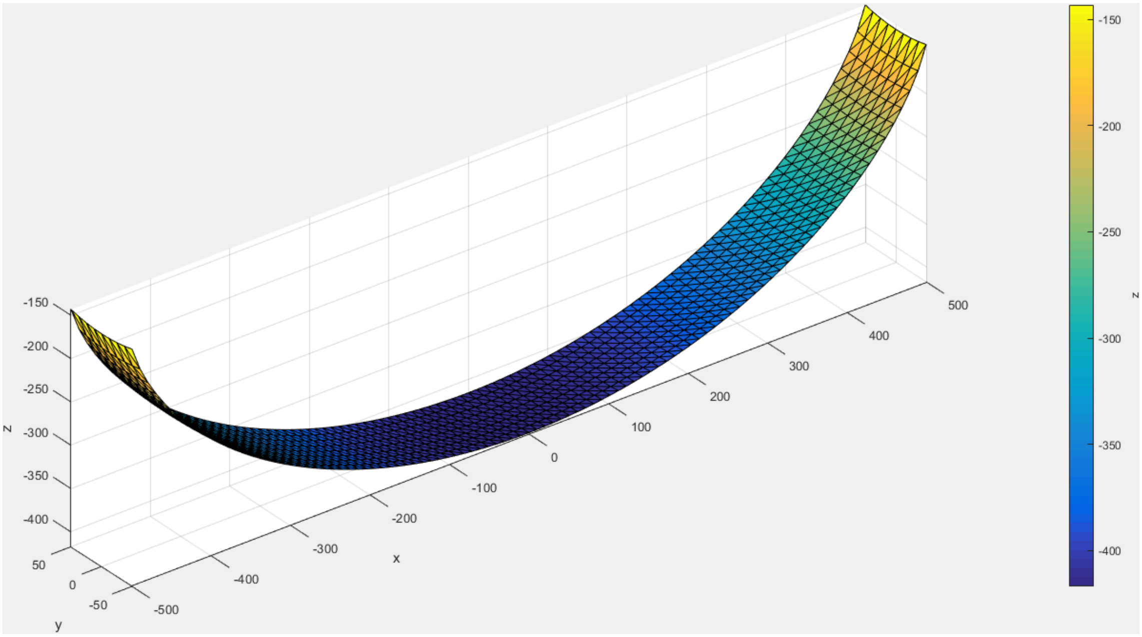


Figure 3.2.: the solar cell is located at z=0 and the light is travelling in positive z direction, continuopus surface, rectangular solar cell, optimised for normal incidence

the light is travelling into positive z-direction. You can see that the surface is bend a lot into the x-direction and hardly bend in the direction of y. It almost looks like the one dimensional solution in x-direction.

In figure 3.3 you can see a projection to the plane of the solar cell. The dark areas in the figure show the contact grid of the solar cell. The figure shows one unit cell. Green dots are the design points and red points are the points the rays are hitting the solar cell. Each design point is connected with the corresponding point the rays hits the solar cell by a red line. You can see that qualitatively the design seems to work well for normal incidence since the design points and the points the rays hitting the solar cell are close to each other. However, for a more quantitative description, let us have a look at figure 3.4. This figure shows the plane of the solar cell. For computational reasons, the surface has been triangulated. The colour of each triangle indicates the distance from the ray at this point to its design point. (see colour-bar on the right side of figure 3.4 for a more quantitative description) The average distance from design point is 1.3 and the number of rays hitting the contact grid is 0. You can also notice that the design works quite well in the middle and quite bad on the edges. (bad performance for high and low x- values)

Moreover, a better three dimensional understanding of the surface is needed. Therefore, let us have a look at figure 3.5a. This figure shows a x/z-projection of the polymer-structure with simulated rays. The light is travelling in positive z-direction. You can see that the rays around x=0 are hardly influenced by refraction and for high or small x-values, the surface of the polymer-structure is bend more and the rays are refracted under a higher angle. Qualitatively, the same happens for the üprojection into y/z-plane. (see figure 3.5b) Notice that the axis of figure 3.5a and 3.5b are not equal. You can see that the surface is bend a lot in x-direction and hardly bend in y-direction. Figure 3.5c shows a three dimensional image of the solar cell located at z=0 and the polymer structure. The light travels in positive z-direction. The contact grid is indicated by the gray rectangulars. The parameters used for this plots can be found in table 3.1. For comparison we computed the annual improvement for all constellations. For optimisation for normal incidence this means a annual improvement of 10.71 %. This is 45,7 % of the maximal annual improvement. In the next step, we search for a design with a as high as possible maximum improvement.

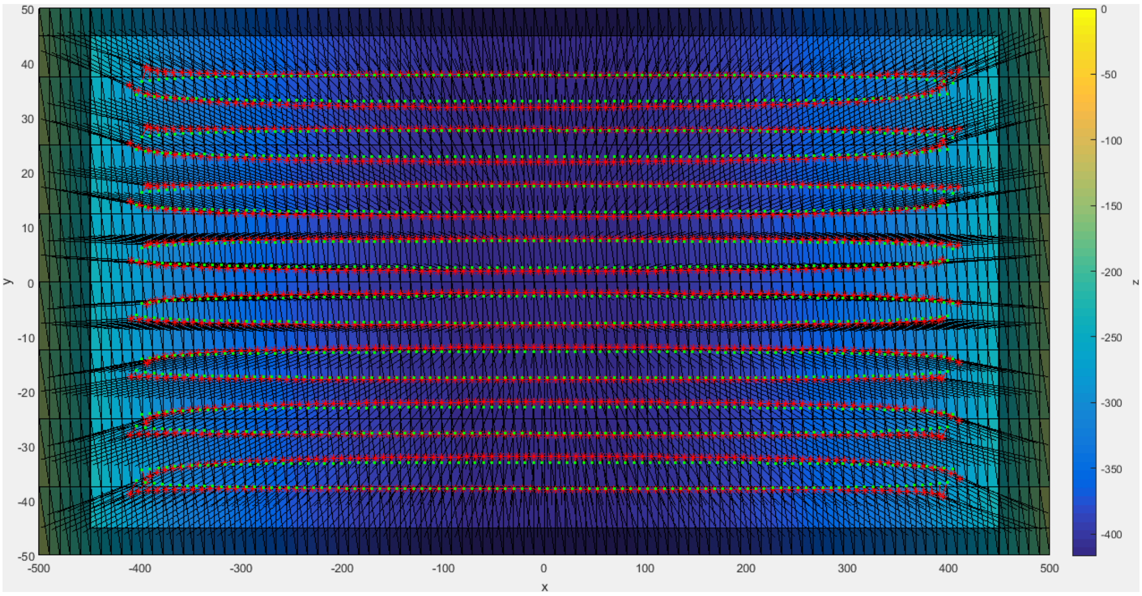


Figure 3.3.: shows the average distance to the designpoint, continuopus surface, rectangular solar cell, optimised for normal incidence

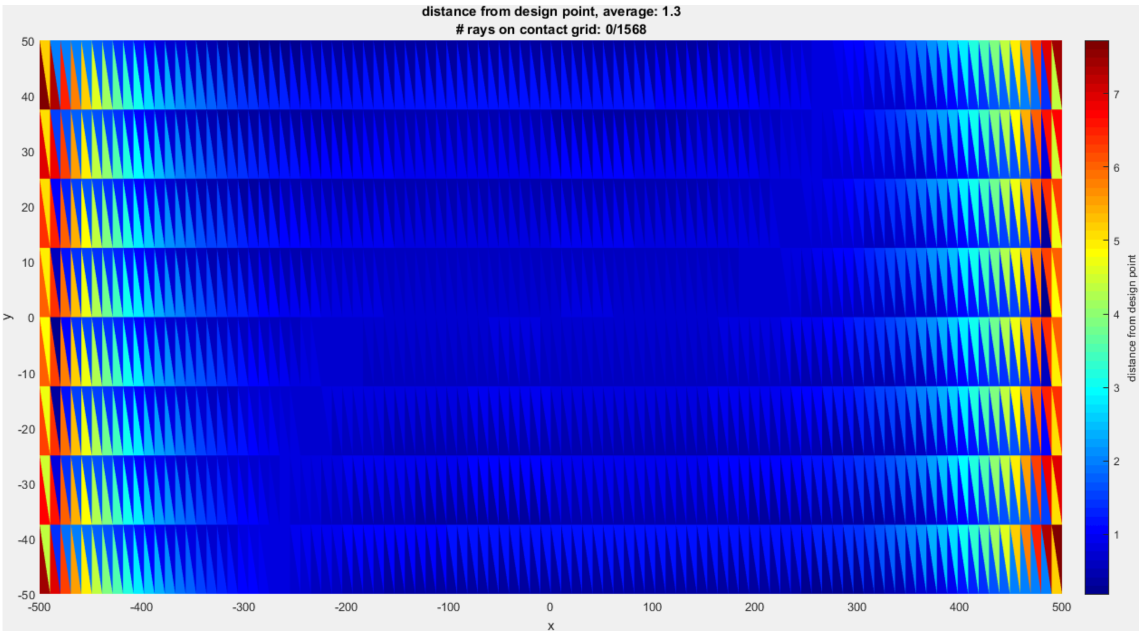
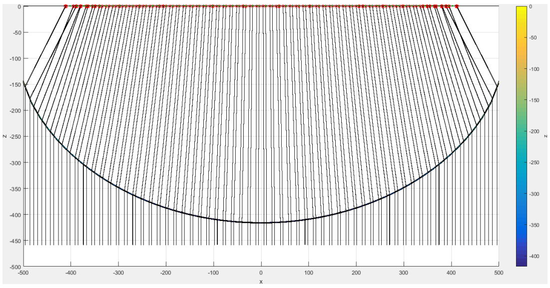
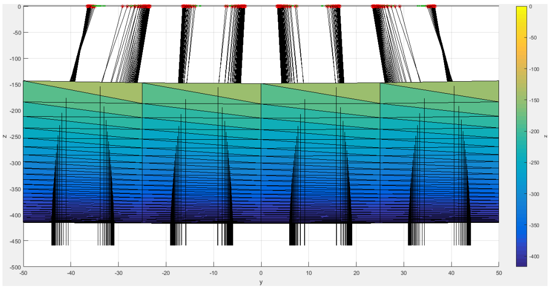


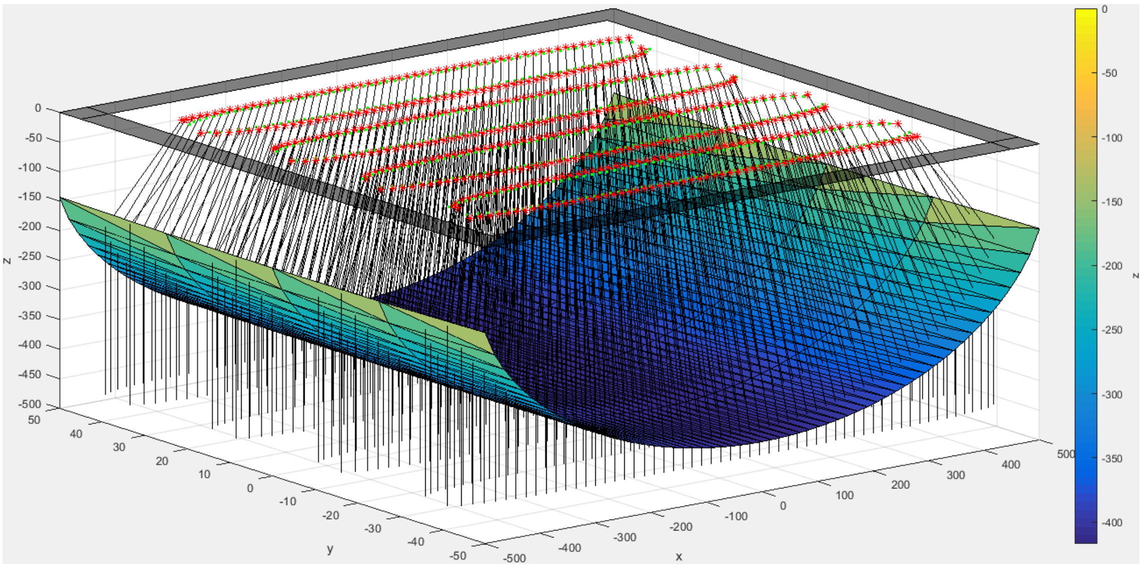
Figure 3.4.: shows the average distance to the designpoint, continuopus surface, rectangular solar cell, optimised for normal incidence



(a)



(b)



(c)

Figure 3.5.: continuopus surface, rectangular solar cell, optimised for normal incidence, the solar cell is located at z=0 and the light is travelling in positive z direction

3.3.2. Optimised for annual improvement

The annual improvement of the surface optimised for normal incident reaches only 46 % of the maximal annual improvement. We will try to enhance the annual improvement. It is possible that the design which works perfectly for normal incident does not give the best results for annual improvement. Therefore, we take the annual improvement itself as value for the fitness of the design. The annual improvement does not take the homogeneity of the light on the solar cell into account. The parameters for optimisation with the annual improvement as fitness can be found in table 3.1. In figure 3.6, we can see the surface of one unit cell. Comparing figure 3.6 (belonging to annual improvement) with figure 3.2 we notice that the figure belonging to annual improvement is bend a bit more in y-direction.

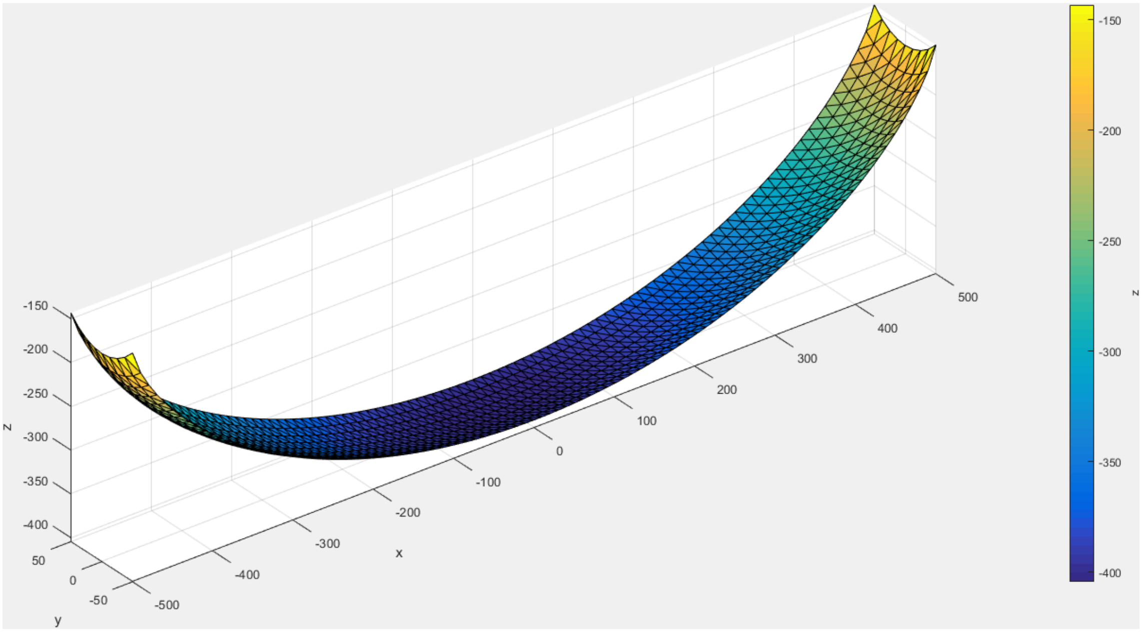


Figure 3.6.: the solar cell is located at z=0 and the light is travelling in positive z direction, continuopus surface, rectangular solar cell, optimised for annual improvement

Similar to the previous chapter, it is useful to look at the average distance to the design point for normal incidence. This can be seen in figure 3.7. The colour indicates the distance to the design point. We can see that it performs bad for small and high y-values. This may be a result of the increase of the bending in y-direction.

However, we can read from table 3.1 that the annual improvement has increased to 11.01 %. This is 46.9 % of the maximal annual improvement. In order to compute the annual improvement, we have to calculate the relative improvement for a few combinations of alpha/beta-values. It is important to take enough values in order to get precise values. By enough we mean a number of alphas/betas for which the annual improvement does stay approximately the same. To demonstrate this effect, we calculated the annual improvement for one parameter-set but two different precisions for the relative improvement. In figure 3.8 the relative improvement for different combinations of alpha and beta is shown. For different betas it works well. However, the relative improvement decreases rapidly around $beta = 10\,\mathrm{deg}$. The reason why we see sort of a periodic up and down for the relative improvement for a variation in alpha for beta=0 is because of the use of periodic boundary conditions. For alpha=12 and beta=0 a lot of rays are hitting the contact grid of the first cell. While increasing alpha, the rays are hitting the optic active area of the next solar cell and the relative improvement increases again. This periodic development does not happen for variation in beta.

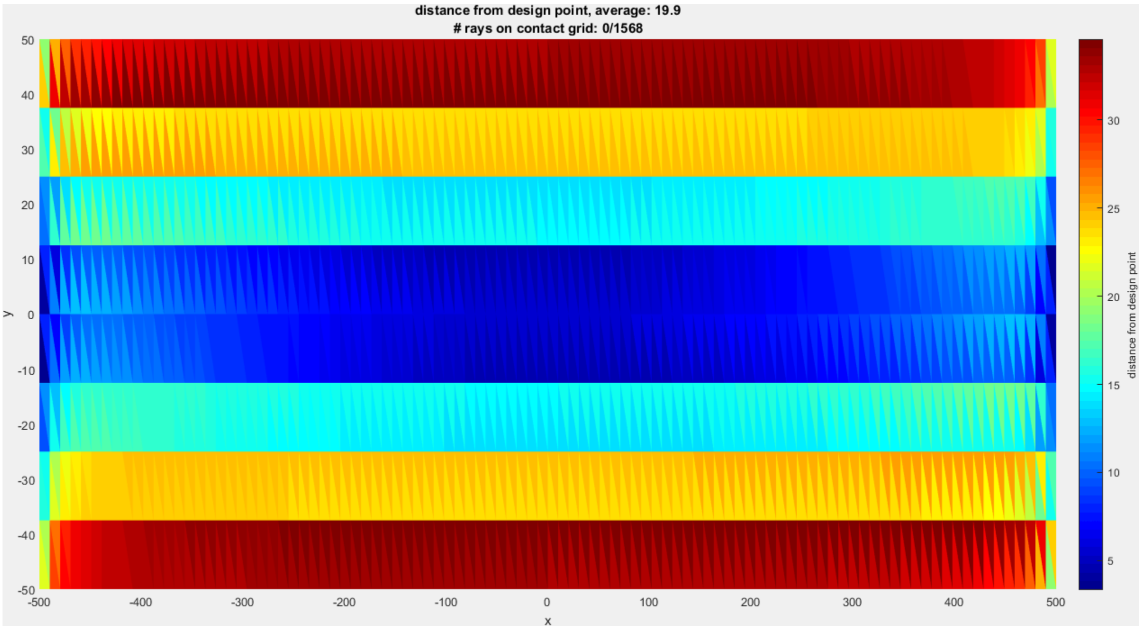


Figure 3.7.: shows the average distance to the designpoint,continuopus surface, rectangular solar cell, optimised for annual improvement

To sum up, the freeform surface design for a rectangular cell works up to maximal 46.9 % of the maximal annual improvement. A cloak only in x-direction leads to an annual improvement of 43.7 % of the maximal annual improvement. Comparing these two values, the gain of cloaking both directions is averaged over one year is 3.2 %.

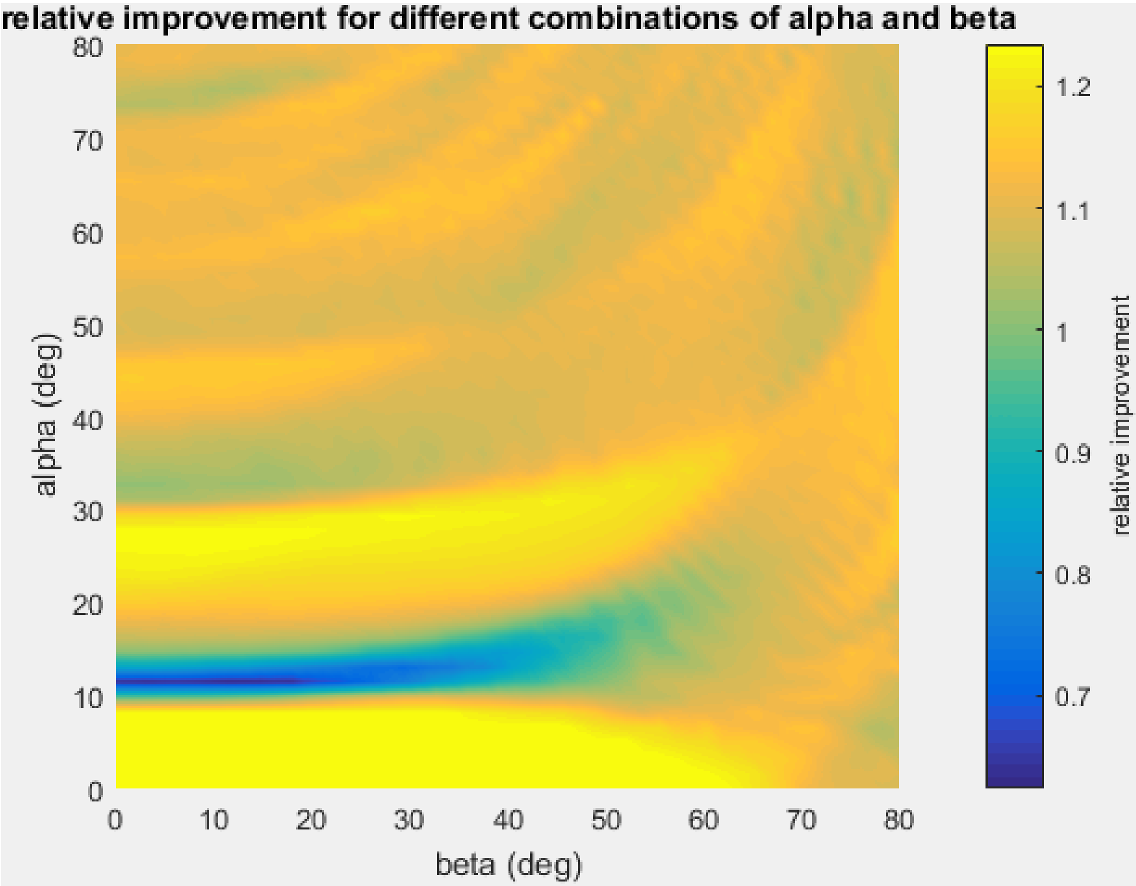


Figure 3.8.: shows the relative improvement for different combinations of alpha and beta, notice that periodic boundary conditions are used to calculate the relative improvement, rectangular unit cell, parameters from optimised for annual improvement are used

3.4. Simulation squared unit cell

In the previous chapter we looked at a rectangular unit solar cell. It worked out that the cloaking in one direction (in x-direction) worked quite well but in y-direction it did not work well. One reason for this could be the asymmetric unit cell. Therefore, we decided to look at a squared unit cell.

3.4.1. Optimised for normal incidence

Similar to the chapter 3.3 we optimised the parameter for normal incidence using the average distance and the number of rays hitting the contact grid as fitness. The surface optimised for normal incidence can be seen in figure 3.9. We notice that the surface is approximately equally bend in x- and in y-direction. Keep in mind that the plots are not plotted with axis equal.

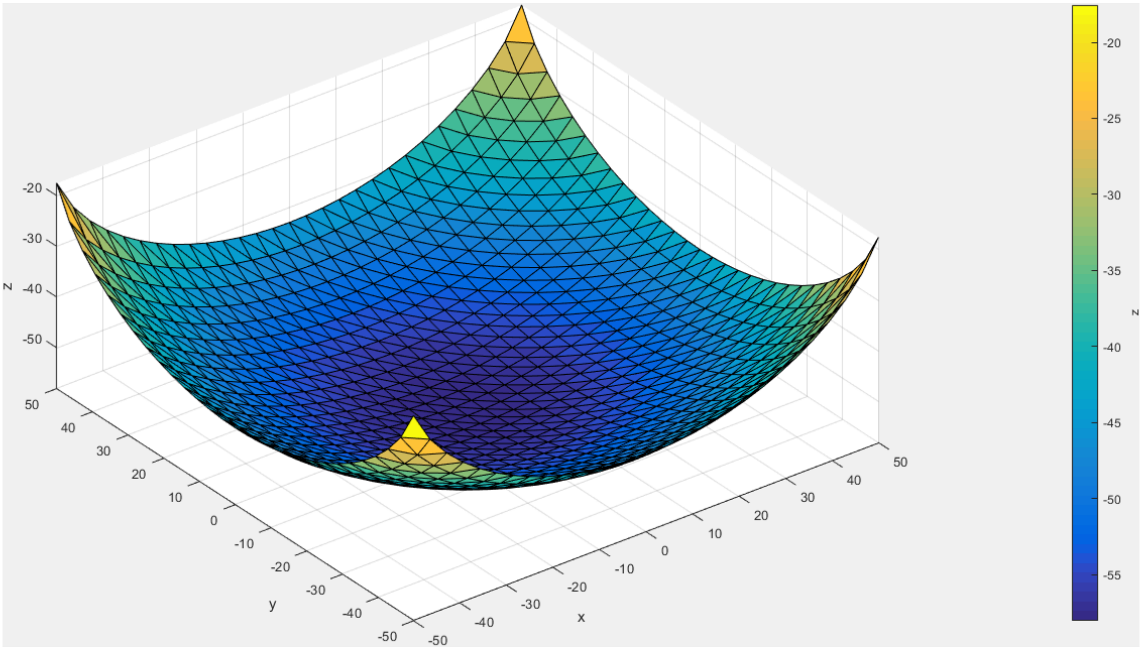


Figure 3.9.: the solar cell is located at z=0 and the light is travelling in positive z direction, continuopus surface, squared unit cell, optimised for normal incidence

Let us have a look at the projection to the plane of the solar cell. This can be seen in figure 3.10. We can see that the design points and the points the rays hitting the solar cell fit nicely together.

Figure 3.11 describes the quality of the design for normal incidence more quantitatively. No ray is hitting the contact grid and in addition to that, the average distance from the design point is 0.4. This is better than the average distance for the rectangular cell (1.3). We can also notice that within the precision of the calculations the average distance is symmetric. (due to triangulation it is not completely symmetric)

The simulations for normal incident for the squared unit cell look promising. Calculating the annual improvement for this design only gives a annual improvement of 2.3 % . This is about 9.5 % of the maximal annual improvement. The parameters used for this calculation and the value for the annual improvement can be looked up in table 3.2.

3.4.1.1. Optimised for annual improvement

We optimised the squared design for annual improvement. (taking the annual improvement as fitness of the design) We reached a annual improvement of 11.5 %. This is about 49.1 % of

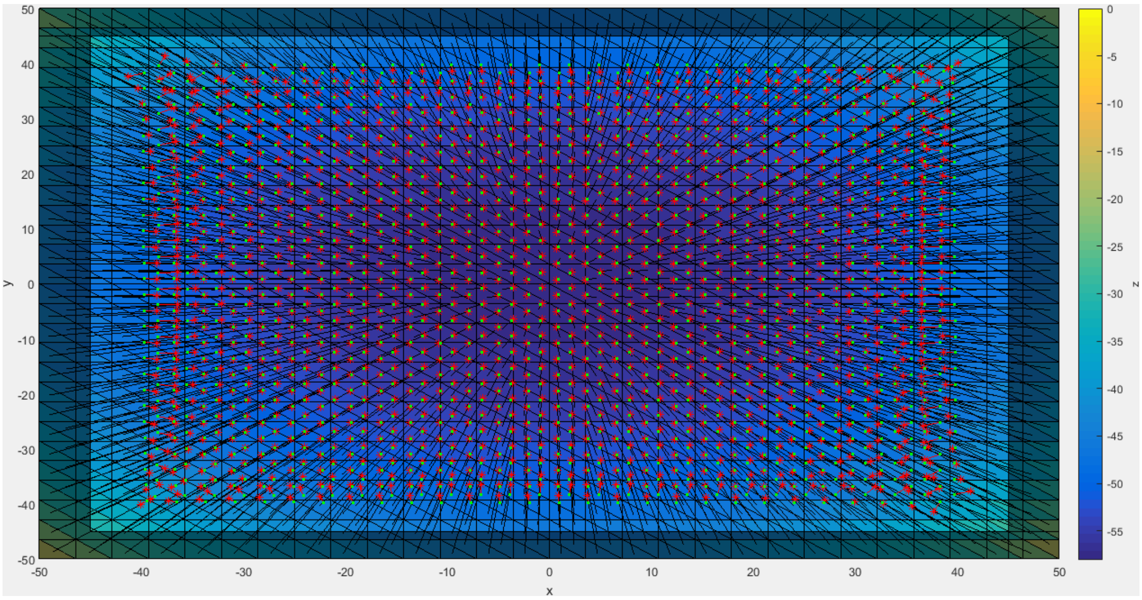


Figure 3.10.: shows the average distance to the designpoint, continuopus surface, squared unit cell, optimised for normal incidence

Table 3.2.: Parameters for simulation for squared unit cell (50 x 50 units)

a	b	y0x	y0y	ξ+1	optimisation	[nalphas,nbetas]
0.6	1.7	5.5	6.0	1.1153	annualImpr.	[10,10]
1.9	1.9	9	9	1.0225	normalinc.	[10,10]
1	0	5	0	1.1019	only f(x)	[10,10]
0	1	0	5	1.1031	only g(y)	[10,10]

the maximal annual improvement. This is a slightly better result as for rectangular unit cell. (as comparison 46.9 % of maximal annual improvement for annual improvement optimisation for rectangular cell) The parameter-set for the squared unit cell can be found in table 3.2. For a better understanding of the angular performance of the relative improvement, have a look at figure 3.12. You can see the relative improvement for different values of alpha/beta-combinations. The plot looks more symmetric in alpha/beta than for the rectangular unit solar cell.

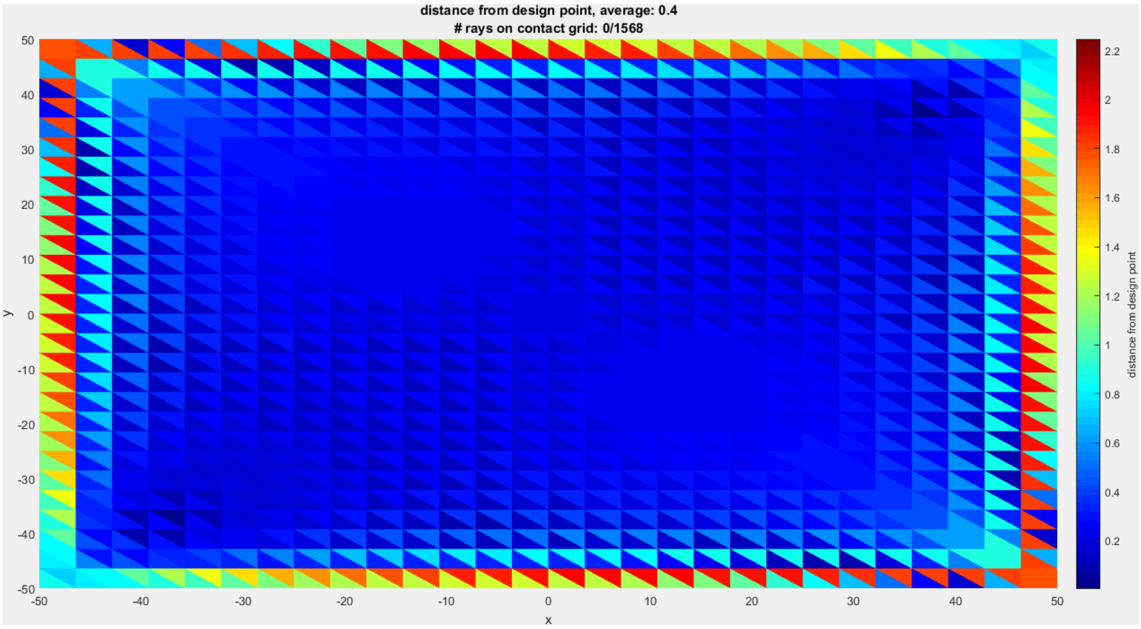


Figure 3.11.: shows the average distance to the designpoint, continuopus surface, squared unit cell, optimised for normal incidence

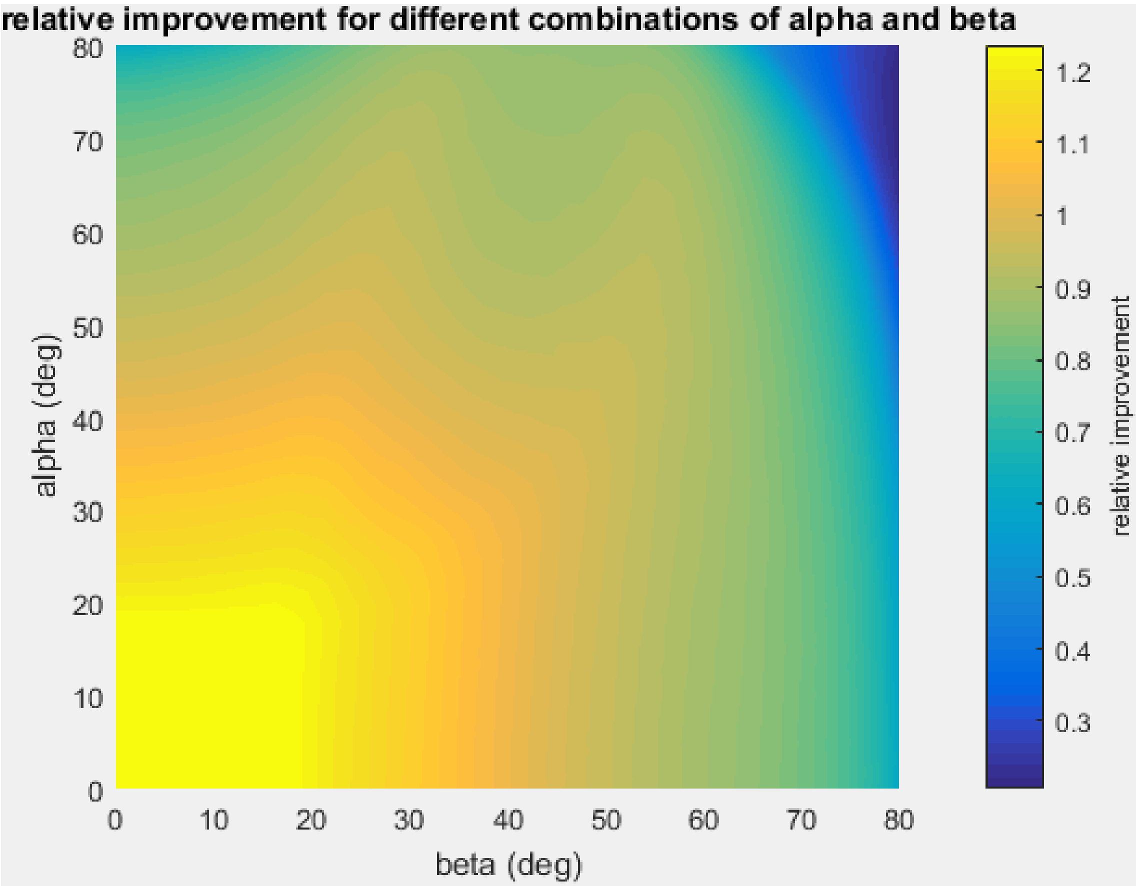


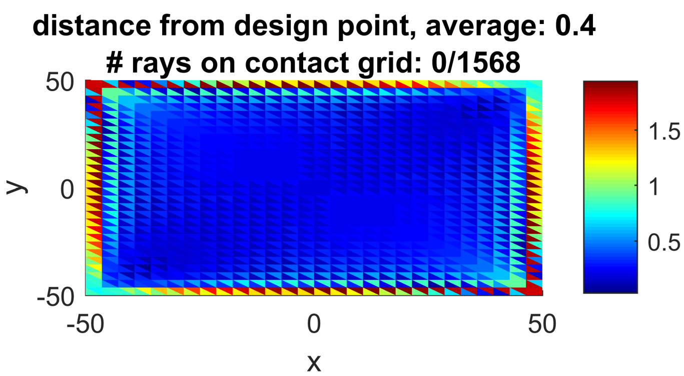
Figure 3.12.: shows the relative improvement for different combinations of alpha and beta, notice that periodic boundary conditions are used to calculate the relative improvement, squared unit cell

4. Simulations for Fresnel design

4.1. Construction of the Fresnel design

4.2. Simulation for rectangular unit cell

4.3. Simulation for squared unit cell



5. Simulations for meta-surface design

5.1. construction of the meta-surafce design

5.2. Simulation for rectangular unit cell

5.3. Simulation for squared unit cell

6. Conclusions

Appendix

A. First Appendix Section

Wonderful Appendix!

Bibliography

[BEK09] Boca, Andreea, Kenneth M Edmondson und Richard R King: *Prismatic covers for boosting the efficiency of high-concentration PV systems.* In: *Photovoltaic Specialists Conference (PVSC), 2009 34th IEEE*, Seiten 000131–000136. IEEE, 2009.

[GSB92] Gee, James M, W Kent Schubert und Paul A Basore: *Emitter wrap-through solar cell.* In: *Presented at the 23rd Institute of Electrical and Electronics Engineers (IEEE) Photovoltaic Specialists Conference, Louisville, KY, 10-14 May 1993*, Band 1, Seiten 10–14, 1992.

[KB06] Kerschaver, Emmanuel Van und Guy Beaucarne: *Back-contact solar cells: A review.* Progress in Photovoltaics: Research and Applications, 14(2):107–123, 2006.

[MSE+16] Mayer, Frederik, Robert Schittny, Amos Egel, Andreas Niemeyer, Jan Preinfalk, Ulrich Lemmer und Martin Wegener: *Cloaking Contacts on Large-Area Organic Light-Emitting Diodes.* Advanced Optical Materials, 2016.

[SWG+15] Schumann, Martin F, Samuel Wiesendanger, Jan Christoph Goldschmidt, Benedikt Bläsi, Karsten Bittkau, Ulrich W Paetzold, Alexander Sprafke, Ralf B Wehrspohn, Carsten Rockstuhl und Martin Wegener: *Cloaked contact grids on solar cells by coordinate transformations: designs and prototypes.* Optica, 2(10):850–853, 2015.

[YC14] Yu, Nanfang und Federico Capasso: *Flat optics with designer metasurfaces.* Nature materials, 13(2):139–150, 2014.

[YGK+11] Yu, Nanfang, Patrice Genevet, Mikhail A Kats, Francesco Aieta, Jean Philippe Tetienne, Federico Capasso und Zeno Gaburro: *Light propagation with phase discontinuities: generalized laws of reflection and refraction.* science, 334(6054):333–337, 2011.

[ZWG90] Zhao, J, A Wang und MA Green: *An optimized prismatic cover design for concentrator and nonconcentrator solar cells.* Journal of applied physics, 68(3):1345–1350, 1990.