Ernst-Abbe-Hochschule Jena
University of Applied Sciences

# OPTICAL INSTRUMENTS LABORATORY REPORT

Ray tracing for optical analysis of solid models

JUNE 20, 2023

Submitted by:
Deepak Petchimuthu (650613)

## 1. Introduction

In contradiction to optical design programs which uses rays which will be affected by Snell’s law in refraction or by reflection TracePro uses “generalized ray tracing”. This technique allows to launch rays into a solid model without any assumption to the order in which objects and surfaces will be intersected. At each intersection, individual rays can be subject to absorption, refraction, diffraction and scatter. As the rays propagate along different paths throughout the solid model, TracePro keeps track of the optical flux associated with each ray. Solid modelling is a technique for constructing computer models of geometrical systems by “solid” pieces of a virtual material. It is gaining wide acceptance among mechanical designers and it’s normally used in computer aided design programs (CAD) for mechanics.

## 2. Theoretical basics

TracePro is based on a specific solid modelling engine called ACIS® , made by Spatial Corporation. Using ACIS® , TracePro can conveniently share solid models with any other programs based on ACIS® . Any entities that will be created in TracePro are referred collectively as a “model”. This model contains some individual pieces of solid geometry what is called “objects”. By using a modelling approach, it’s necessary that all objects are bounded by surfaces. Any object can be defined within TracePro, or it can be defined in a CAD program and imported into TracePro. A classical optic design program calculates the propagation of light from one surface to the next and so on. This may require enormously complicated software programs. TracePro uses the Monte Carlo method to simulate all possibilities wherever the light can propagate. This means every time diffraction, reflection and scatter is calculated, too. The Monte Carlo method is a technique for computing the outcome of a random process. Scattering and diffraction of light are treated as a random process. Instead of propagating a distribution of light, discrete samples of the distribution, or rays, are propagated. These samples are randomly chosen. Using this way, you’re able to calculate much more rays as you can do by calculating the exact propagation of each ray.

**Task 4.1: Build an f/4-lens with a focal length of 100 mm and analyse the ray trace and the intensity distribution at the image surface. Therefor you need to define a detector and you can use the irradiance map. Define a source in front of this lens that the rays are leaving the lens parallel to the optical axis.**

For the modelling of the lens in TracePro, we first need to calculate the geometrical dimensions and size of the lens. For the ease of modelling, we can choose either bi-convex lens of a plano-convex lens. We chose the plano-convex lens.

For the Plano-Convex lens:

$$\frac{1}{f'} = \frac{n-1}{R}$$

For n=1.5 of lens material chosen from the module, and focal length of 100 mm, we get the radius,

$$\mathrm{R{=}50\ mm}$$

The height of lens from the optical axis can be calculated as below:

$$2\rho = \frac{f'}{4} = \frac{100}{4} = 25\,mm$$
$$\rho = 12.5\,mm$$

We add another 1mm to this half height for mounting clearance. With that we get $\rho = 13.5\,mm$

For the calculation of the lens size, we need its thickness. For that we need surface sag,

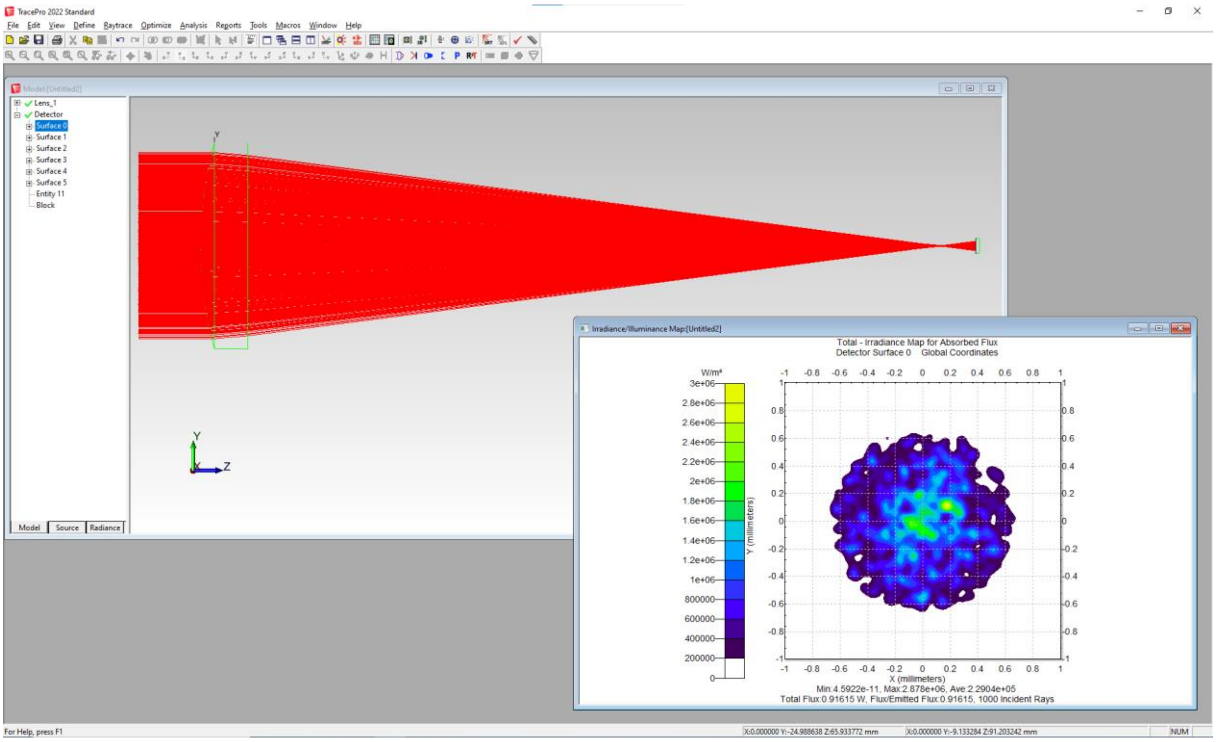
$$z = R - \sqrt{R^2 - \rho^2}$$
$$z = 50 - \sqrt{50^2 - 13.5^2}$$
$$z = 1.8569\,mm$$

The total thickness of the lens will be the sum of edge thickness and surface sag.
Edge thickness should be at least $1/10^{th}$ of the diameter of the lens.
so the edge thickness will be 25/10= 2.5 mm
Therefore,

$$th_c = z + th_e$$
$$th_c = 1.8569\,mm + 2.5\,mm$$
$$th_c = 4.3569\,mm$$

According to the mentioned dimensions, we create a lens in the optimizer of TracePro and then export it to TracePro.

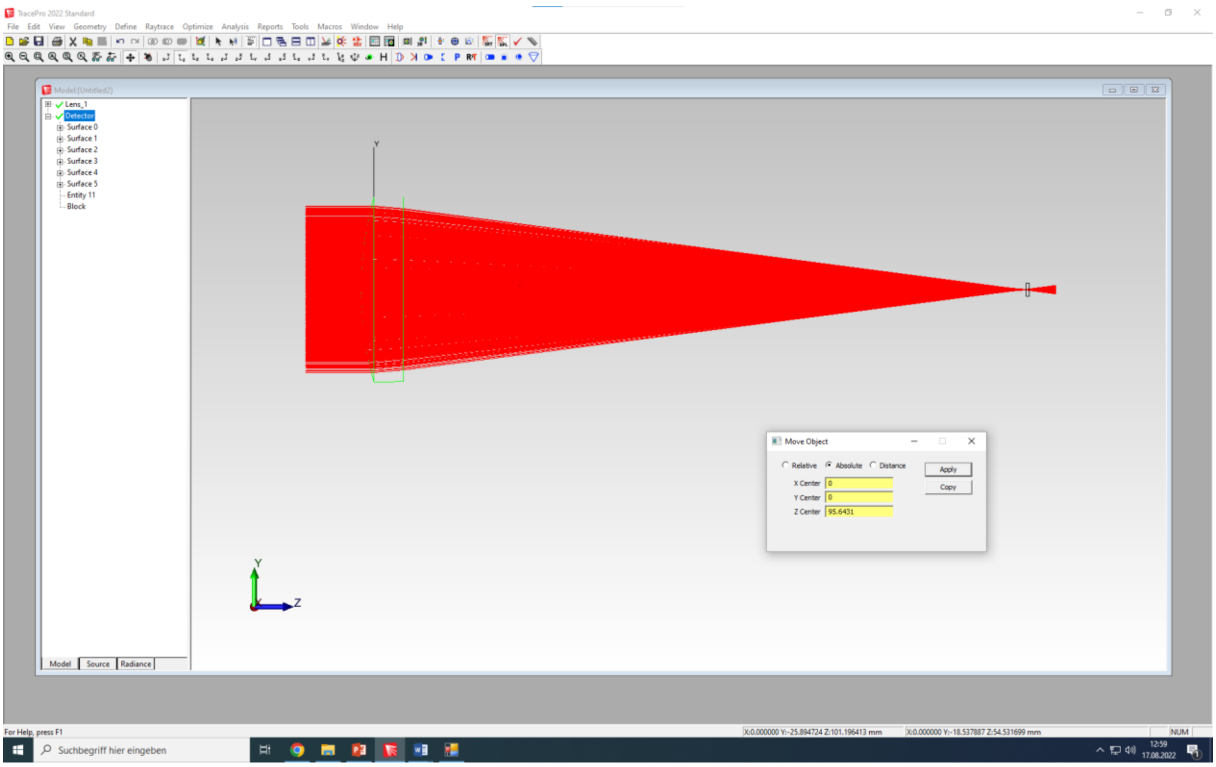
Originally, we place the detector on 100 mm in Z-direction, which gives us the irradiance map like this:



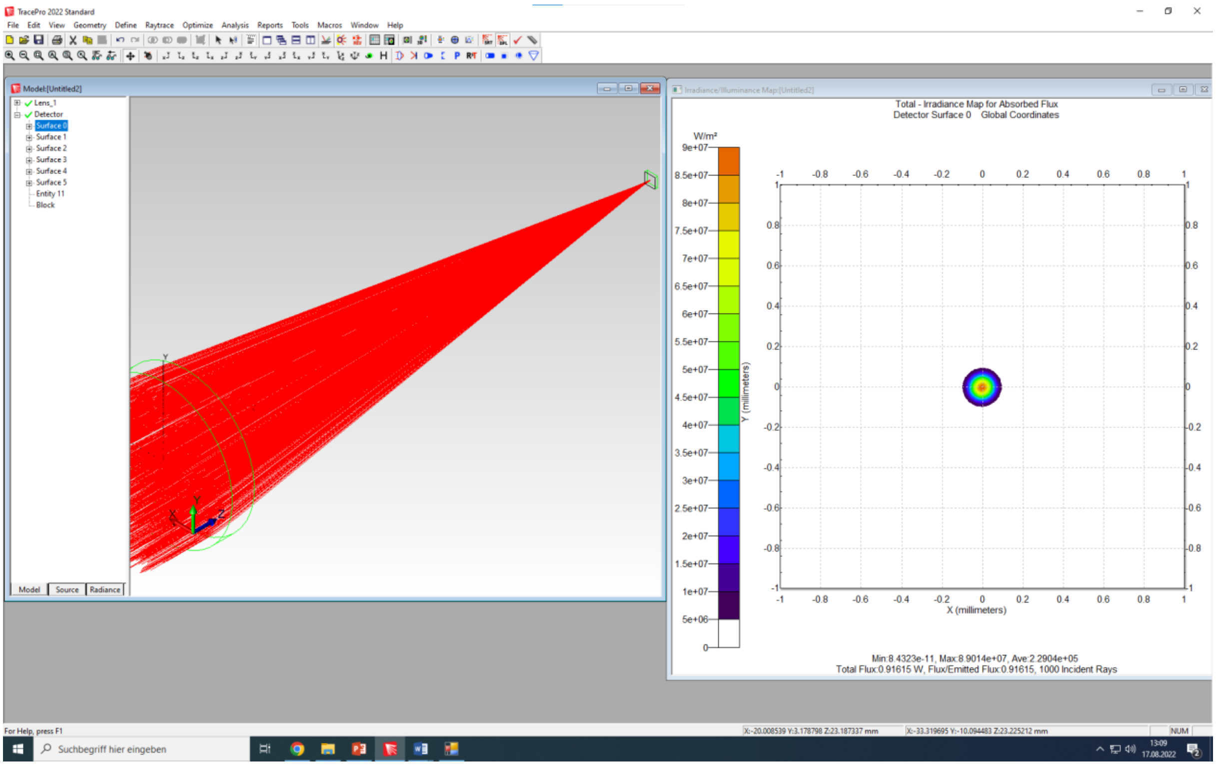

At this position, the rays are not converged. So, we try to get the irradiance map at focus.

Since focal length of the lens is 100 but the plano-convex lens has a thickness of 4.3569 mm, the effective length of convergence, where the actual focus will be obtained, will be 100-4.3569 = 95.6431mm.

So we move the detector with the distance as shown below:



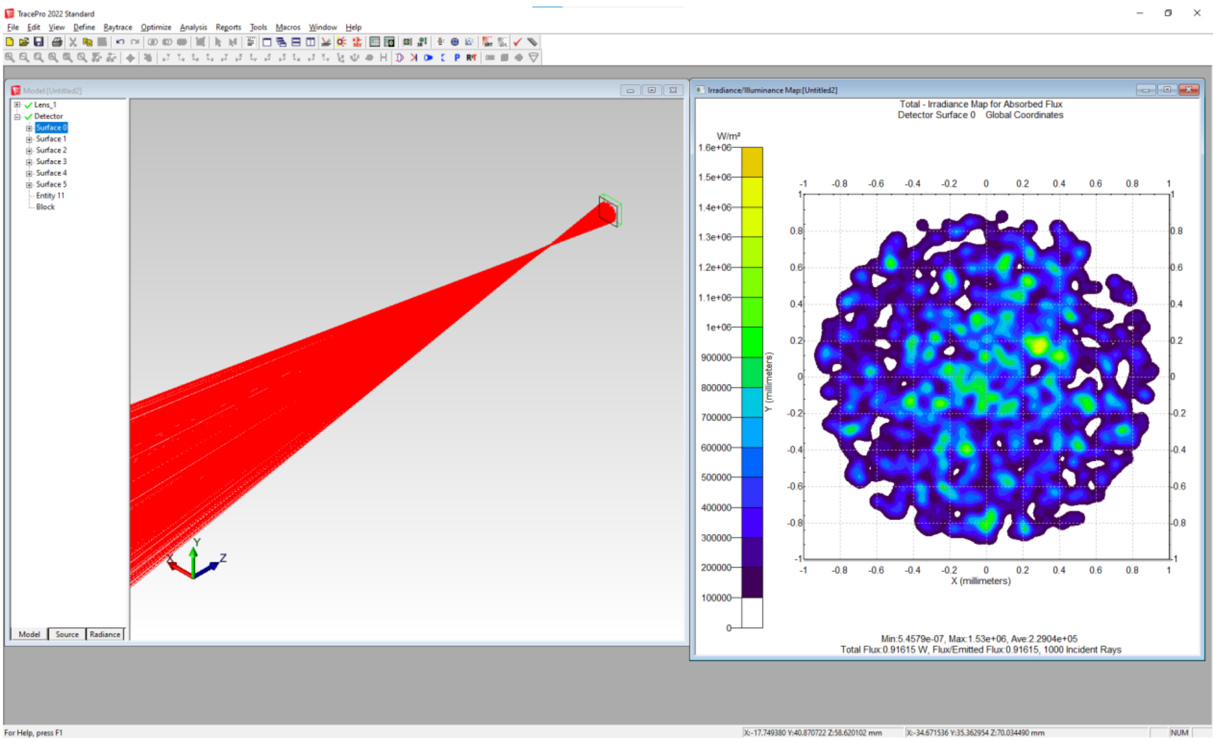

This gives us the **irradiance map at focus** as shown below:



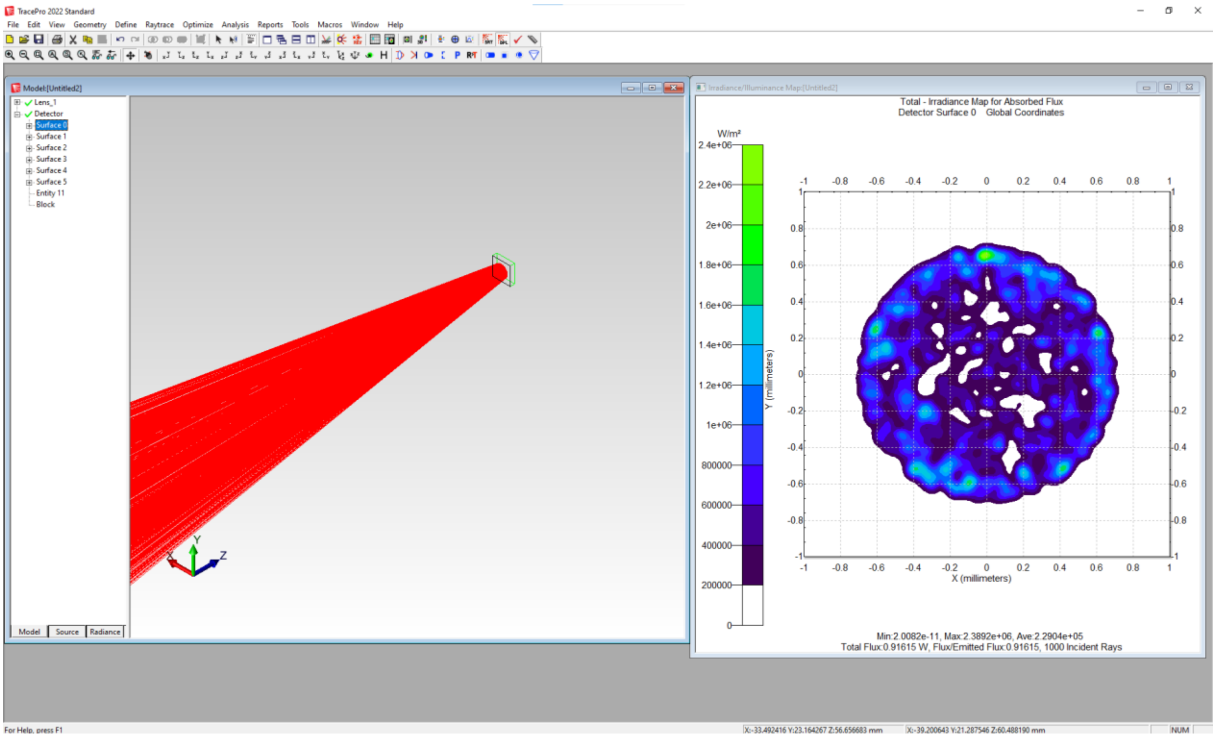

## Effect of Defocus:

The effect of defocus is simply the act of the image not being in the focus. This will result as a blurred image or unclear edges. The image at focus is precise and clear to distinguish. In TracePro, this can be observed by changing the detector position from focus to the positions that are not in focus, which means before or after the convergence of light rays.

The irradiance map after the focus looks as shown below:



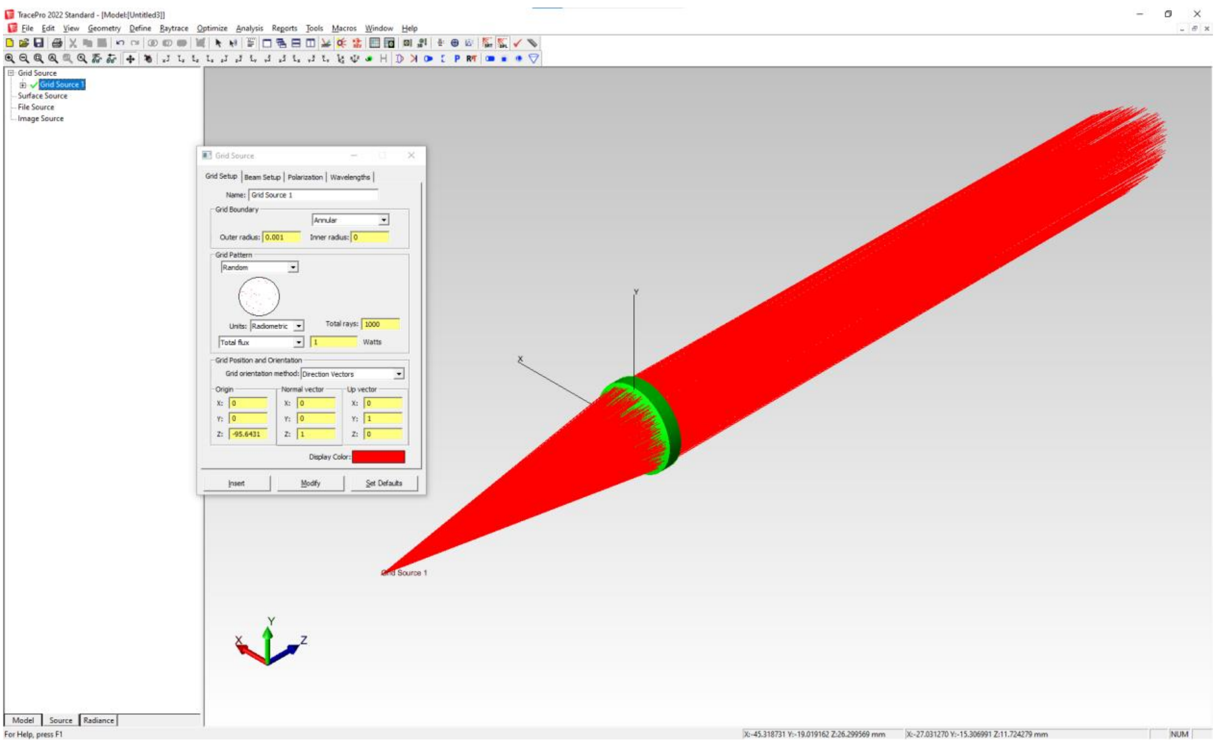
Similarly, the irradiance map before the focus looks out of focus like below:




**<u>Light rays leaving the lens parallel to optical axis:</u>**

For achieving this, we need to put a point light source at the focal length distance from the lens in object side. We need to modify two things for that:

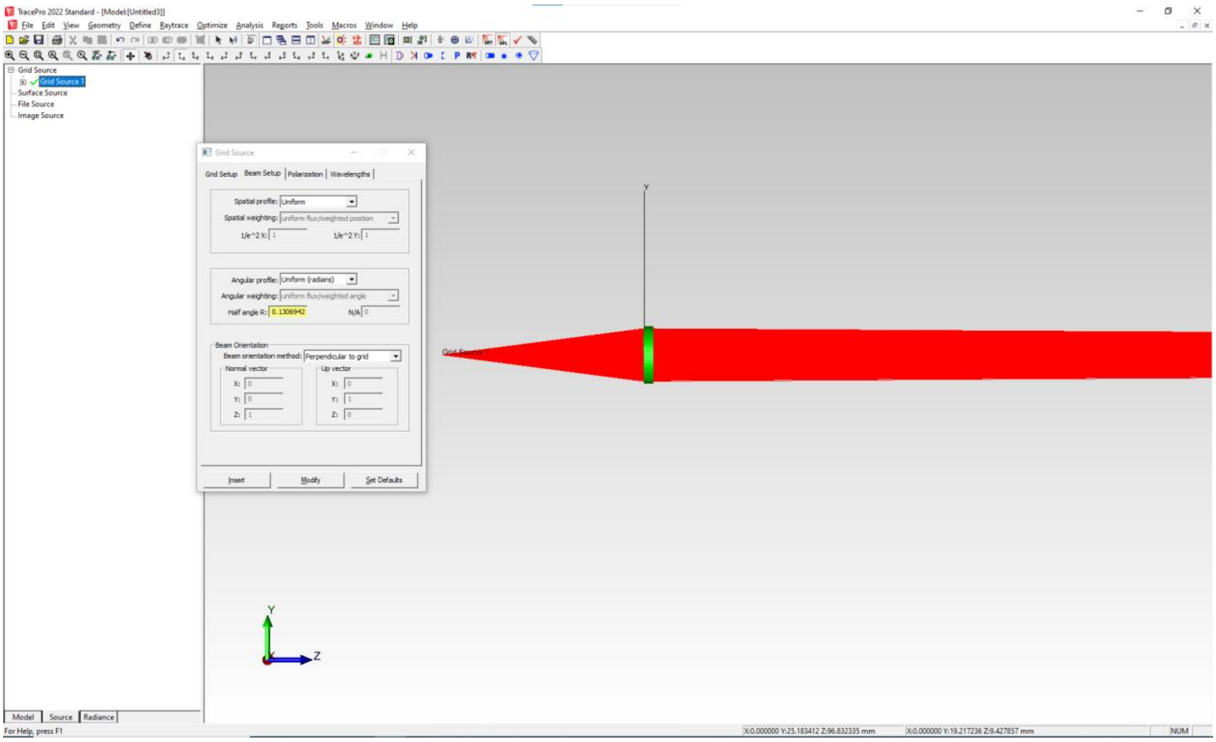
1. The position of the light source (at focal length): The focal length of the lens, where the rays were converged in the previous case was 95.6431mm. The same length is used as the position for point light source.



2. The light source's size and orientation: the light source should be a point source and therefore it's size also has to be small. For that, we use 1µm as the outer radius of the light source. Additionally, we will have to adjust the emitting angle of the light source. We can do that by calculating tan for the half angle and using paraxial approximation.

Since ρ= 12.5, we get,
$\tan\alpha \approx \alpha = 12.5/95.6431 = 0.130694$

We use this angle as the half angle for emittance. This can be seen in the image below:

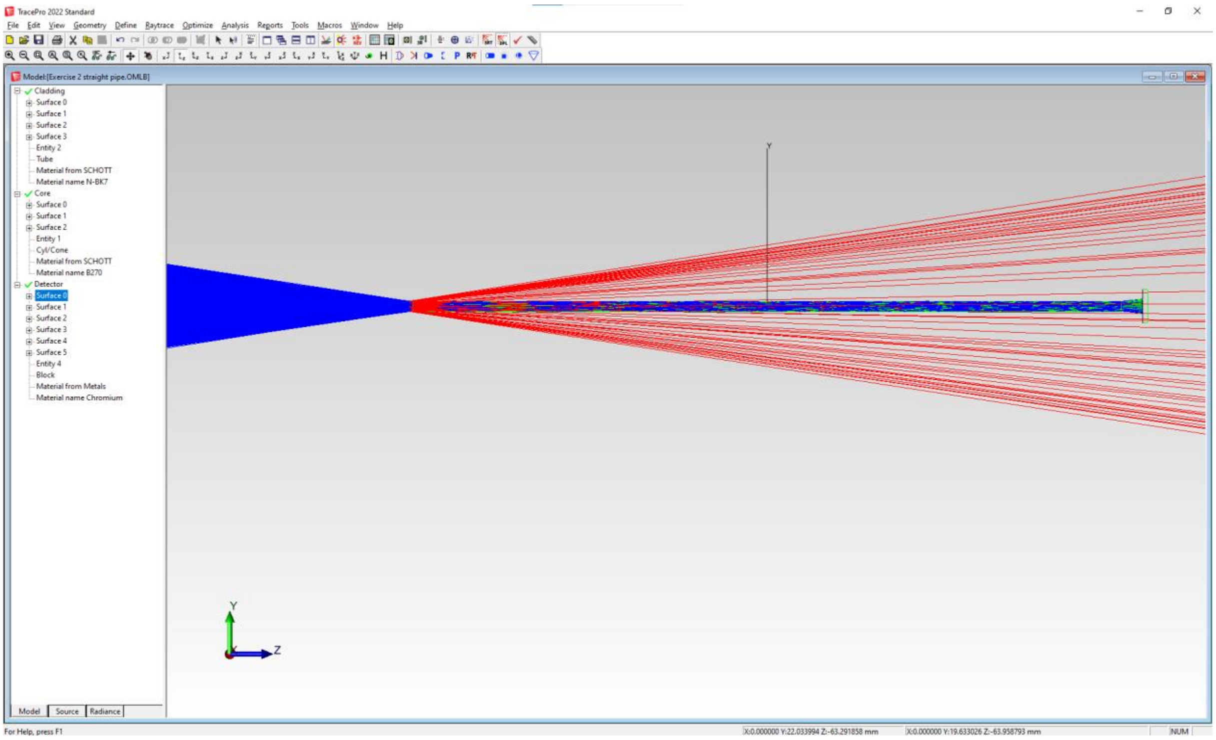


As can be seen from the above image, the emitting rays from the lens are almost parallel to the optical axis. However, it can be seen that the rays do converge to a small degree in longer distances. This can be due to a number of possible reasons such as using paraxial approximation, limitation of the software itself to cope with the scenario. But the deviation from the expected behavior is fairly small, therefore, it can be neglected.

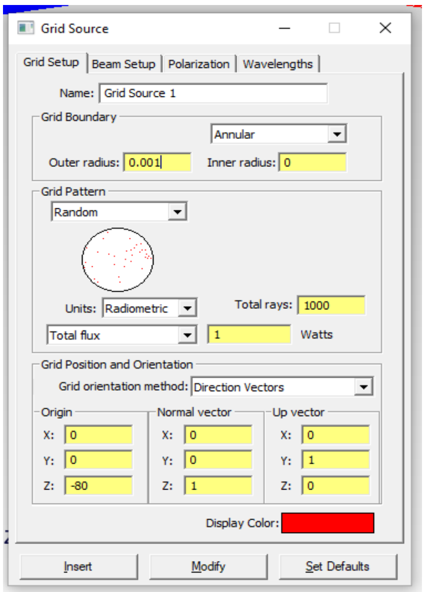
**<u>Task 4.2:</u> Create a light-pipe with a core diameter of 1.5 mm and a length of 150 mm. The cladding should have a thickness of 0.3 mm. For the cladding you're using N-BK7 and the core is variable: B270 or N-BAK4. Start with a straight pipe consisting of cladding and B270-core. Define a source in front of the pipe that the pipe is guiding the light properly. Bend the pipe 90° and decide if it's necessary to change the glass type for the core. Find out the smallest possible radius to get at least 90% of the incident energy at the end of the bended light-pipe.**

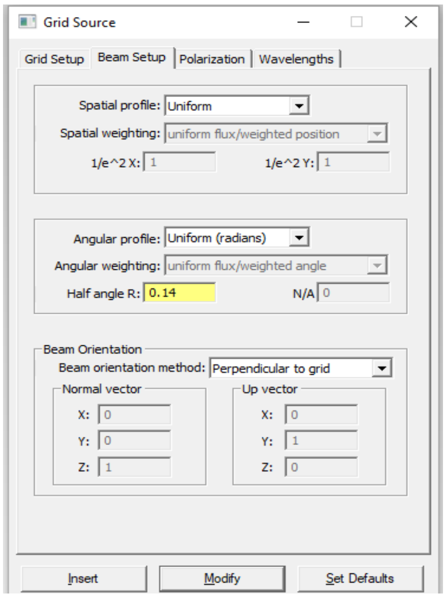
The light optical fiber was created by making a hollow core using a primitive solid of cylindrical shape with the given diameter of 1.5mm and a surrounding cladding was made as a tube around it with the same inner diameter and thickness of 0.3mm. The material was assigned as well.

In the first attempt of raytrace, we get the following output:

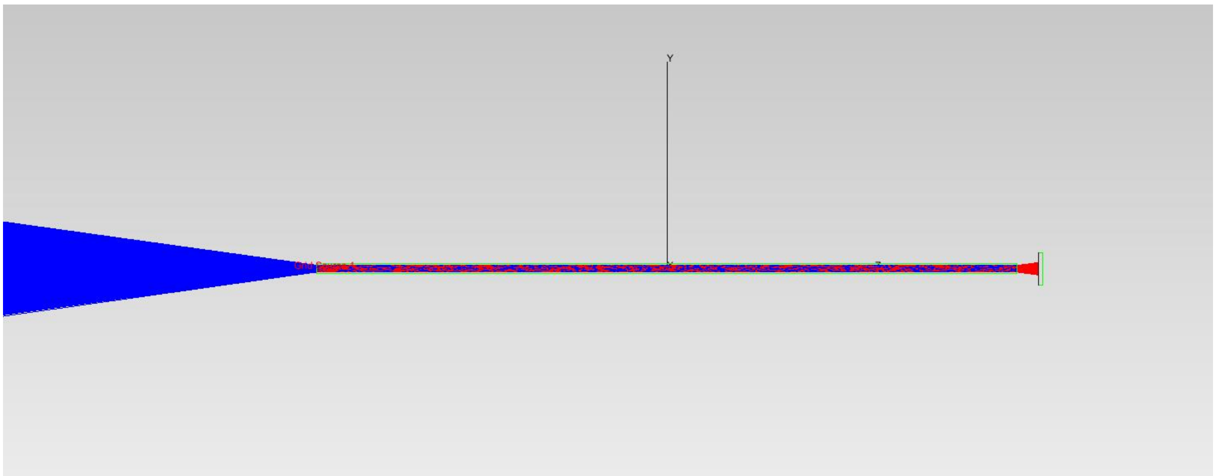



There are a *few problems* with this raytrace though.
The first is that the source is too big in respect to the tubes and emits light on wider angle than needed. So, we first solve that by making the source a point source and giving it the angle of emittance.
The angle of emittance can be calculated by, (1) acceptance angle of the optical fiber or (2) using geometrical calculation and paraxial approximation of the angle.
For ease of calculation, I use the latter approach. The corrections for the source are shown below:



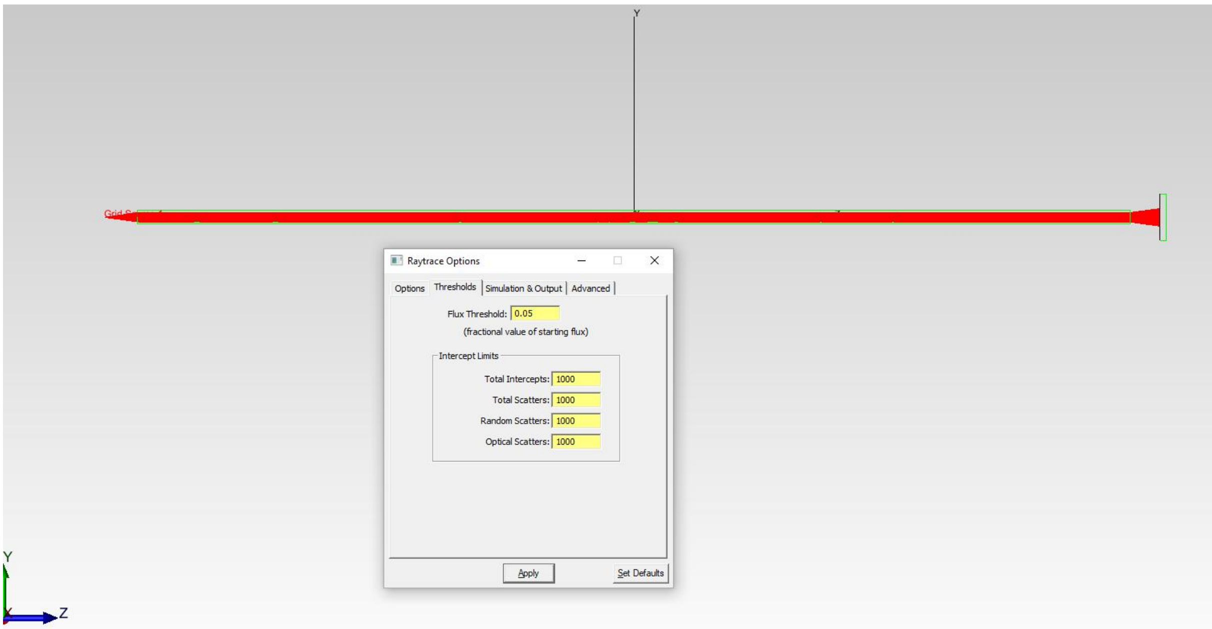
The changes can be seen in outer radius and Half angle R of the source.
With these modifications, we reach at:




There is still a problem.

The figure is mostly occupied by the blue light, which is the back reflected light. We can work better without this much light. We can achieve that by two approaches:
1) increasing the flux threshold value.
2) using anti-reflection coated surfaces.
Here I demonstrate the former approach.

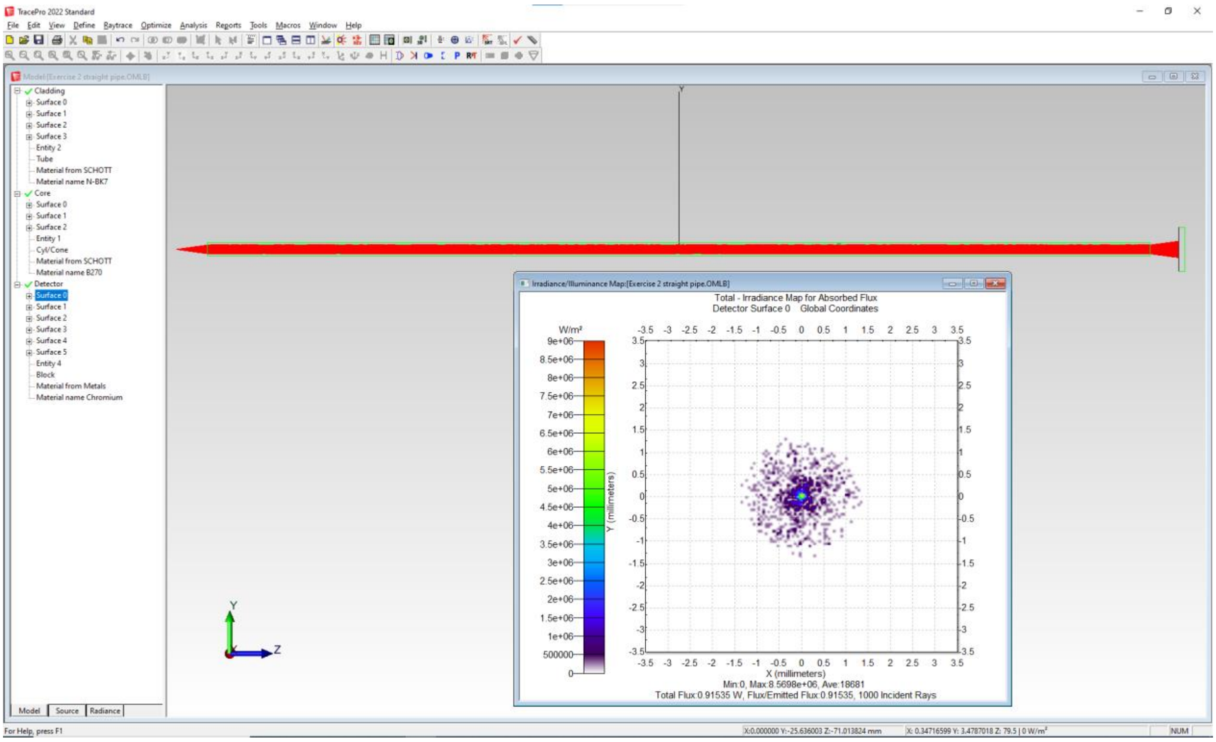
The threshold value is the deciding factor of what light rays would be displayed in raytrace. Rays started by TracePro from a source are traced and split until the flux carried by a ray component is below the threshold. At that point, that branch of the ray tree is terminated. So, to eliminate the blue light rays, we increase the value of flux thresholds from 0.2 to 0.5. This will filter the rays and will leave us with lesser blue stray rays.



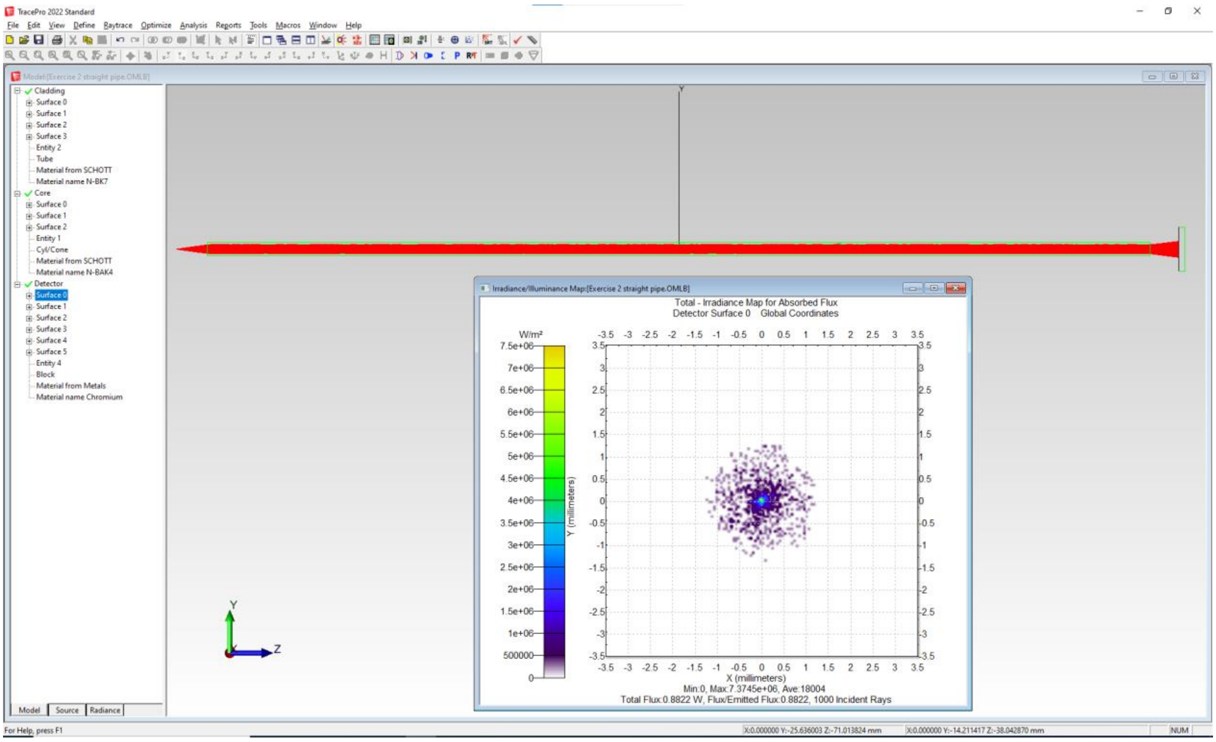

This is a suitable and more interpretable representation of the optical fiber.

Now, we change the material of the core as given in the problem. The cladding material remains same namely, N-BK7.

**Core material B270**:

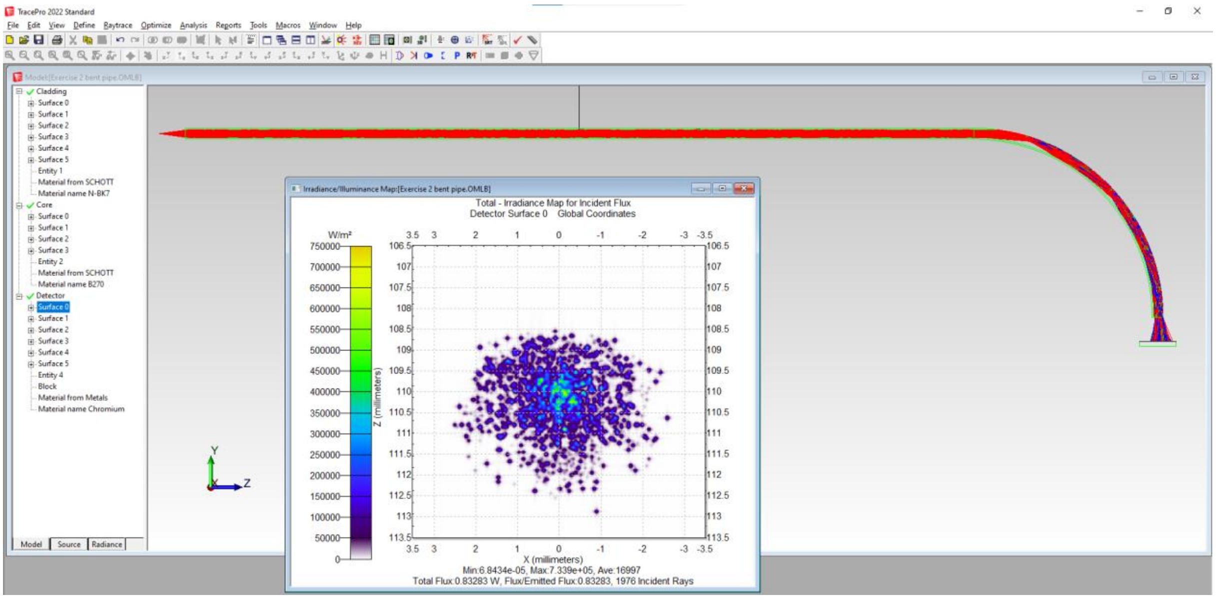



**Core material N-BAK4:**

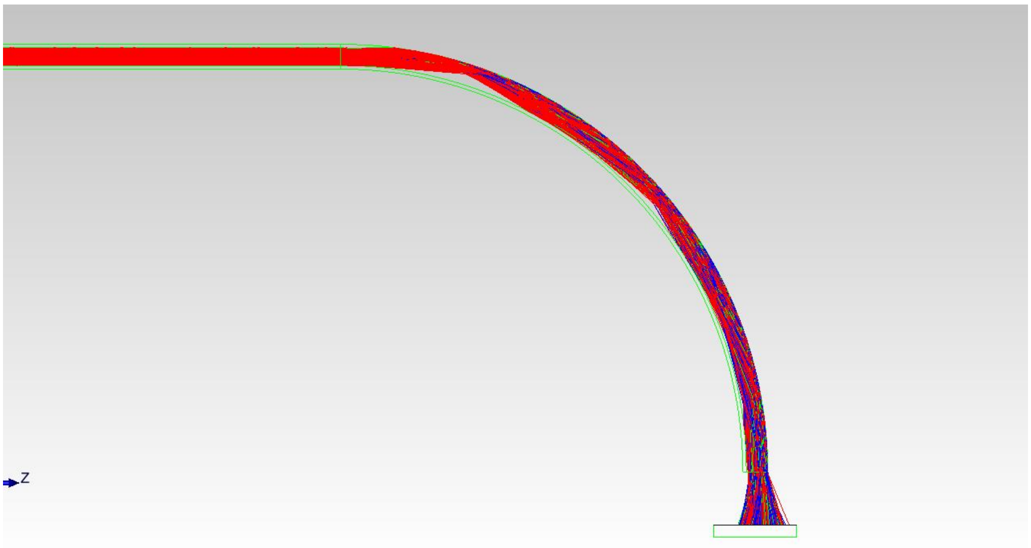


In the straight pipe, both the materials work quite fine. In detail, we can see that B270 does give us a better energy transmission through the tube than N-BAK4, but the difference is not very drastic.

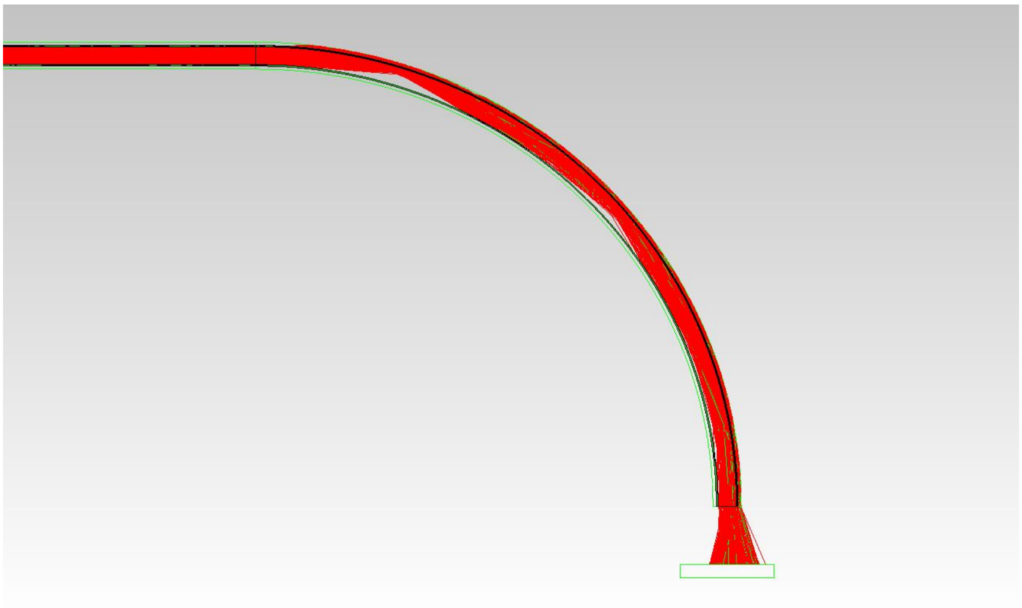
**<u>Bending the pipe:</u>**




Now, while using B270 for the core material, it seems fine. But if we look closely at the bend, we observe that the light is not passing through just the core, but it breaks the boundary and travels though the cladding too, which is not the desired behavior of the optical fiber. This can be looked in the image below:

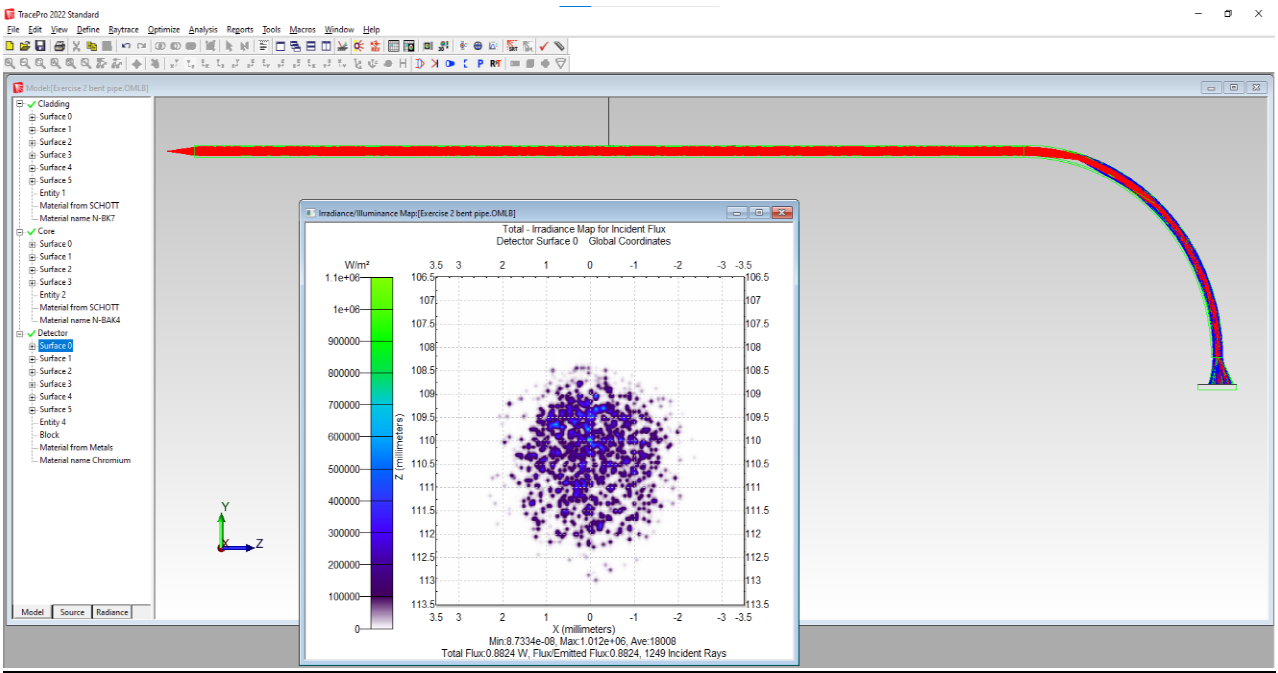



Even after removing the blue light, we get:

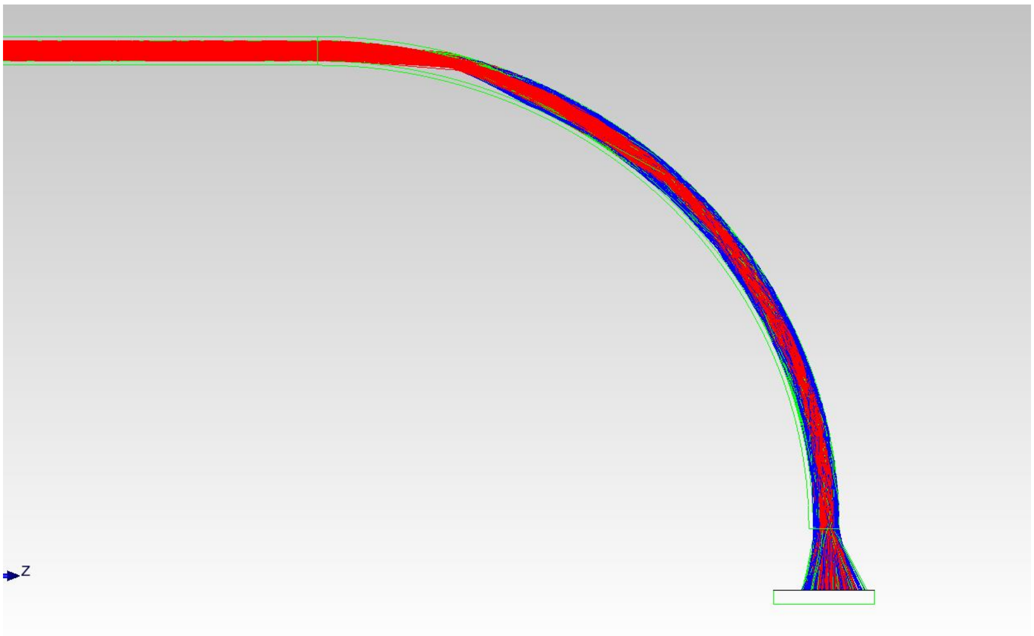


This material is therefore, <u>not a good option</u> for core.

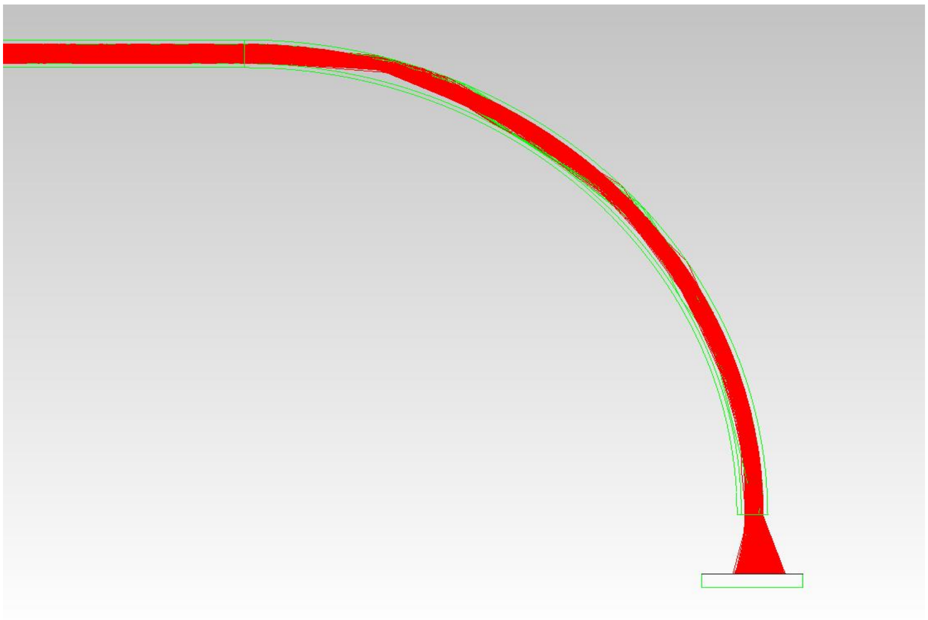
Trying the same with core material as N-BAK4 gives us something like this:



Zooming in on the bend:




This can be seen that in the cladding there are still some rays but they are back-reflected rays. We can enhance this by using coated surface for the bend or further increasing the flux threshold. After increasing flux threshold, it gives us:



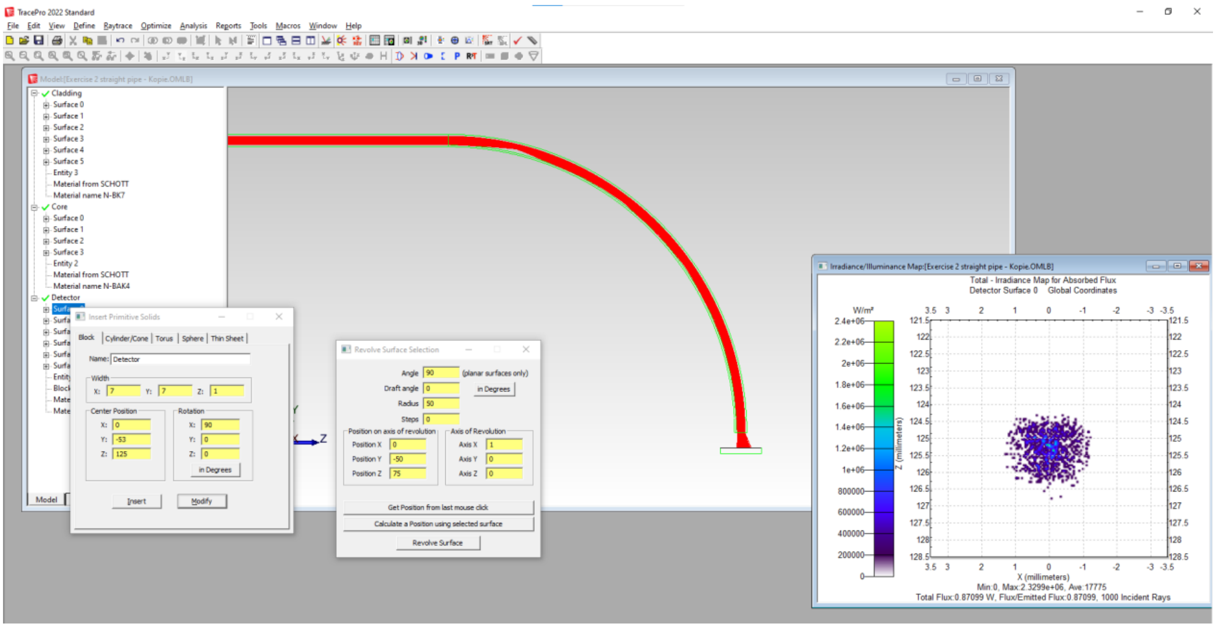
So thus, it can be seen that for bending of the pipe, it is necessary that the material of the core be changed to N-BAK4. N-BAK4 has a higher refractive index and therefore provides better material for optical fiber's core and facilitates better Total Internal Reflection.

**<u>Obtaining 90% energy transfer:</u>**

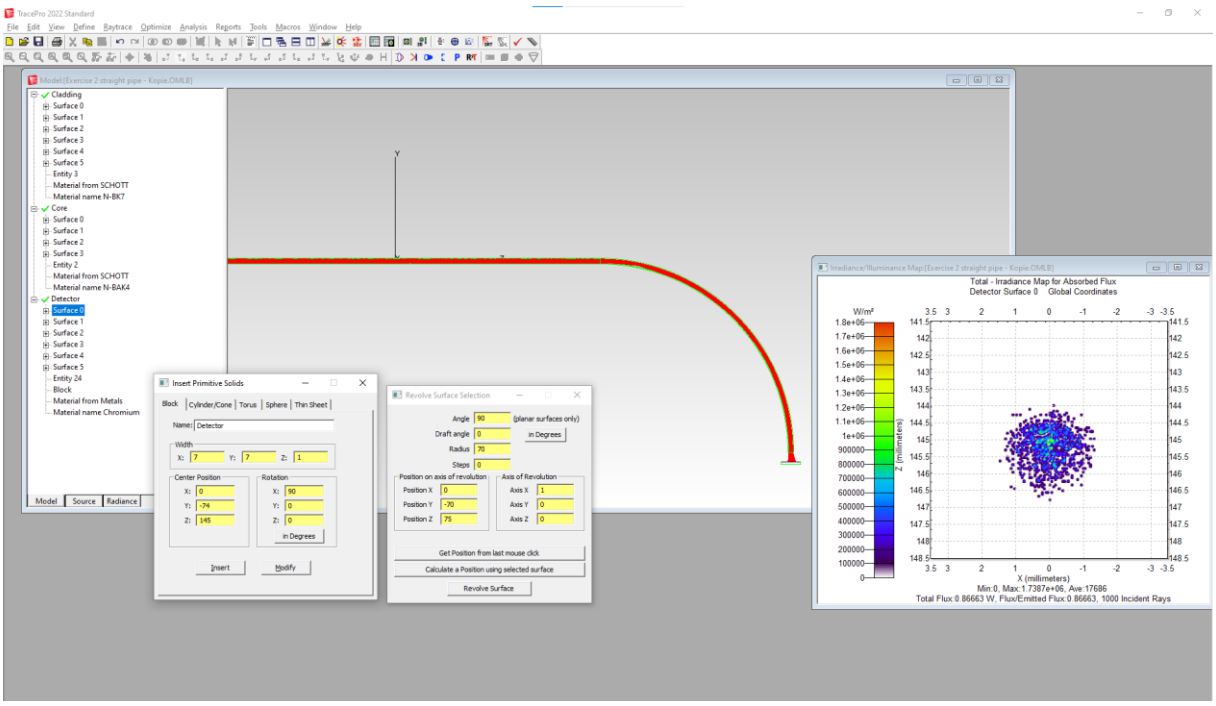
The minimum radius for which we get 90% energy transfer can be observed from irradiance maps for different radiuses. Using TracePro, we bend the fiber on different radiuses but keeping the bending

angle same as 90°.
While defining the source, we gave the input energy as 1 Watt and the transmitted energy can be seen down in the respective irradiance maps.

We observe that at about 50mm radius we get the transmitted energy as 0.87 Watt, which is about 87% of the input flux energy. This is almost close to the desired value.

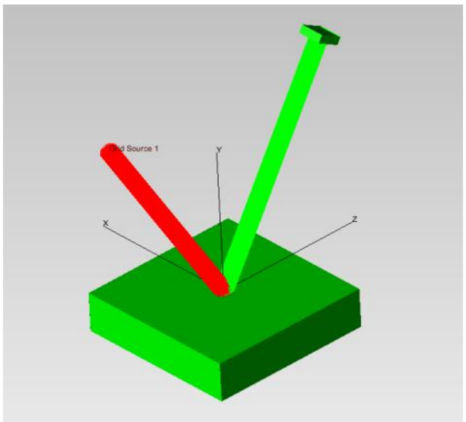


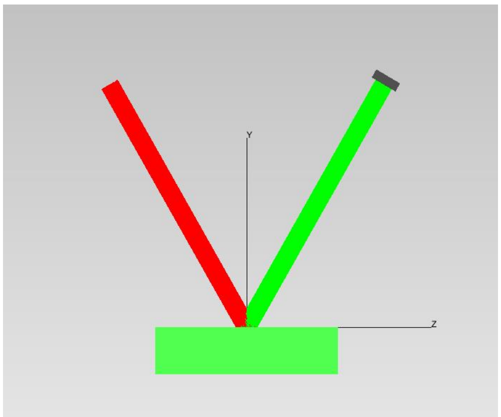

Further increasing the bend radius does not give any significant improvements.



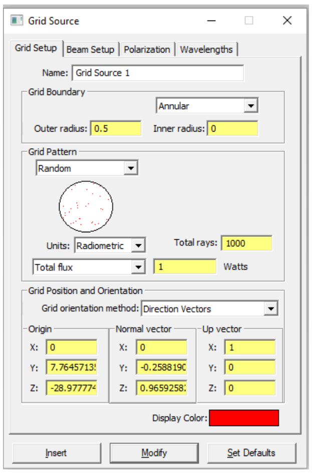

**Task 4.3: Define a sample consisting of Titanium. Illuminate this sample with linear polarized light with an oscillation angle of 45 degree. Find out the main angle of incidence and show the polarization ellipse. Name the values for the describing angles for ellipticity and orientation.**

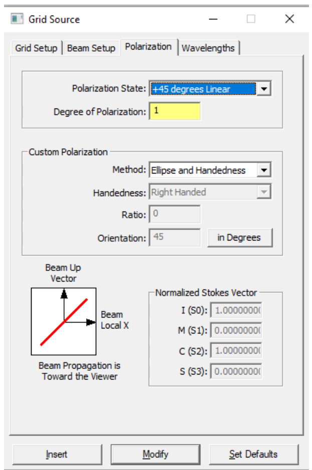
The arrangement of Titanium sample illuminated with polarized light is shown below:



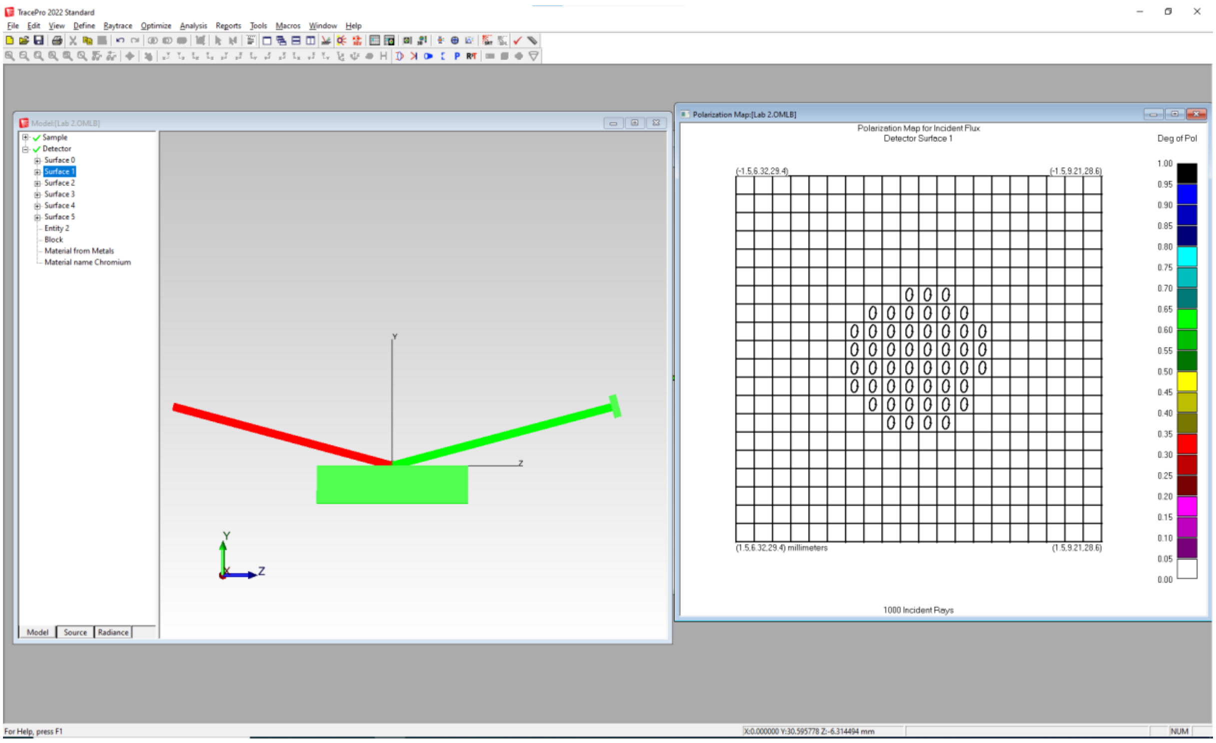

While defining the light source, we give it polarized light as emittance on the block of Titanium. In addition to that, we take note of the normal and up vectors. We see that the normal vectors are in Y and Z direction, while the up vector is in X direction.




We gave the incidence of +45° polarized light on the Ti sample.

For the evaluation of the main incidence angle, we have to draw the polarization maps of the illumination system. We do the same and change the up vectors and normal vector of the desired view of polarization map.
The main angle of incidence is that angle what gives a phase shift of pi/2 between the perpendicular and parallel part of the reflected light. The result is an ellipse in its so called “normal shape”, means the orientation of the major axis is equal to the x-axis and the minor axis is oriented along the y-axis of the coordinate-system.
In TracePro, we may give the normal and up vectors manually, but we can also select the option for TracePro to automatically calculate normal and up vectors and align them into representation. We select that option and look at the polarization map.
We try with different angles of light source and place the detector accordingly. On the angle of 75° from vertical, we get a polarization map which looks like shown below:




While looking at this orientation of the ellipses, it may seem wrong, but this is the correct orientation for the main incidence angle, because the drawn maps coordinates are -X in upper direction and +Y in right direction. So, our ellipse has its major axis along X-axis and minor axis along Y-axis i.e., it is in its normal shape. This is corresponding to the angle of 75° from vertical axis. So, we get the main angle of incidence as 75°. The corresponding values can be seen in the polarization map options.

**References:**


1. https://www.lambdares.com/wp-content/uploads/TraceProDownload/TracePro_User_Manual.pdf
2. F. Pedrotti, Introduction to Optics; ISBN-10: 0131499335