



# PHOT 451: Microscale optical system design

## LECTURE 03

*Michaël Barbier, Fall semester (2025-2026)*

# OVERVIEW OF THE COURSE

week	Topic
Week 1	Introduction to micro-scale optical components
Week 2	Light propagation in free space
Week 3	Geometric optics and raycasting
Week 4	Diffraction limit & Abberations
Week 5	<b>Quiz</b> + Beam propagation
Week 6	Refractive optical elements Microlenses
Week 7	Blazed Fresnel lenses
Week 8	Digital lenses
Week 9	Diffractive optical elements
Week 10	<b>Quiz</b> + Wave guides and beam propagation
Week 11	Wave mixing
Week 12	Gratings, periodic structures
Week 13	photonic crystals
Week 14	Whole optical system optimization



# Geometrical Optics (Ray Optics)

# GEOMETRIC OPTICS

- Light path: straight line in homogeneous medium
- Refractive index:

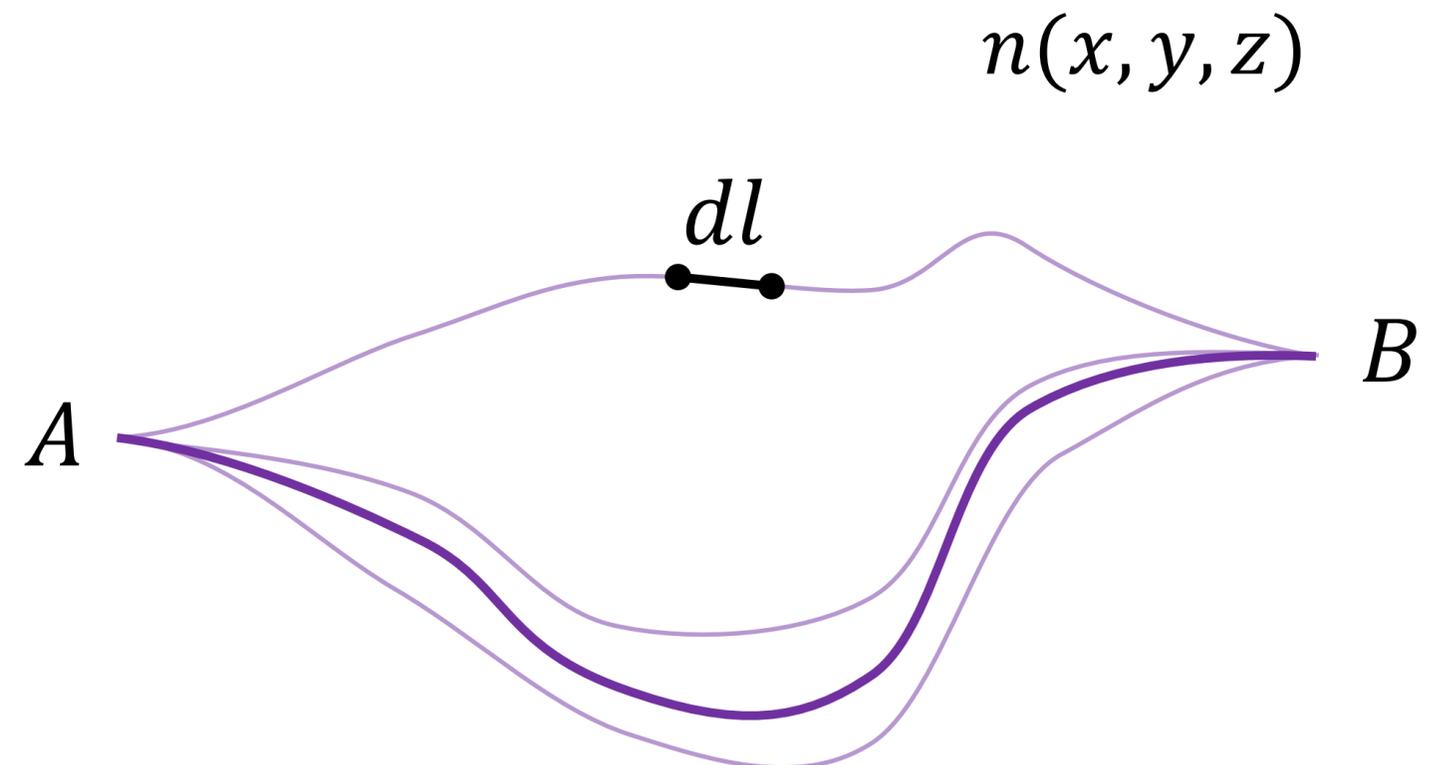
$$n = \frac{c_0}{v} = \frac{\text{velocity vacuum}}{\text{velocity medium}}$$

- Optical path length:

$$\text{OPL} = \int_A^B n(x, y, z) dl$$

- Fermat's principle:

$$\delta \left[ \int_A^B n(x, y, z) dl \right] = 0$$



# GEOMETRIC OPTICS & RAY-TRACING

- Phase local wavefront (eikonal)

$$\varphi(\mathbf{r}) = \mathbf{k} \cdot \mathbf{r}$$

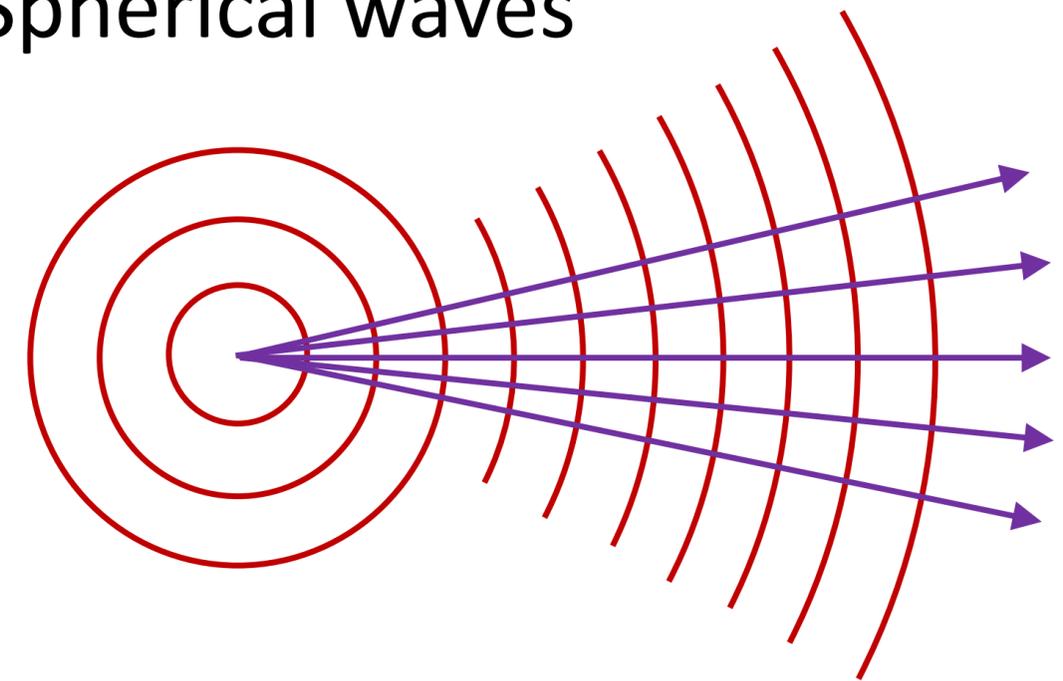
- Wavefront: line constant phase
- Light rays perpendicular to wave fronts

Parallel rays  
Point source



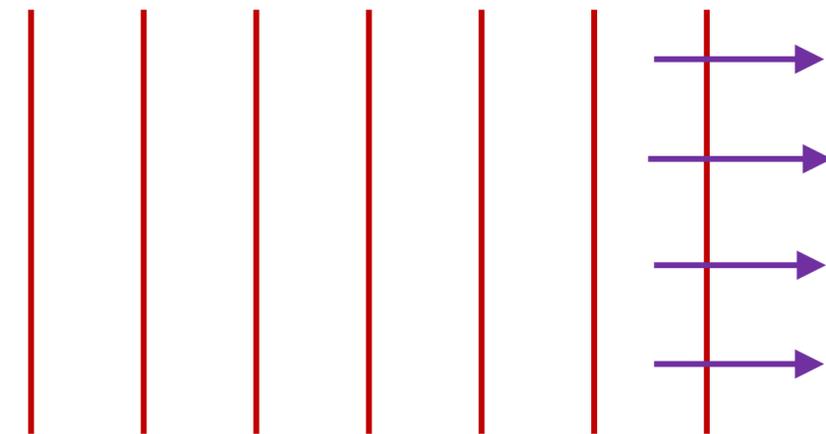
Plane waves  
Spherical waves

Spherical waves



Rays follow  
local  $\mathbf{k}$  vector

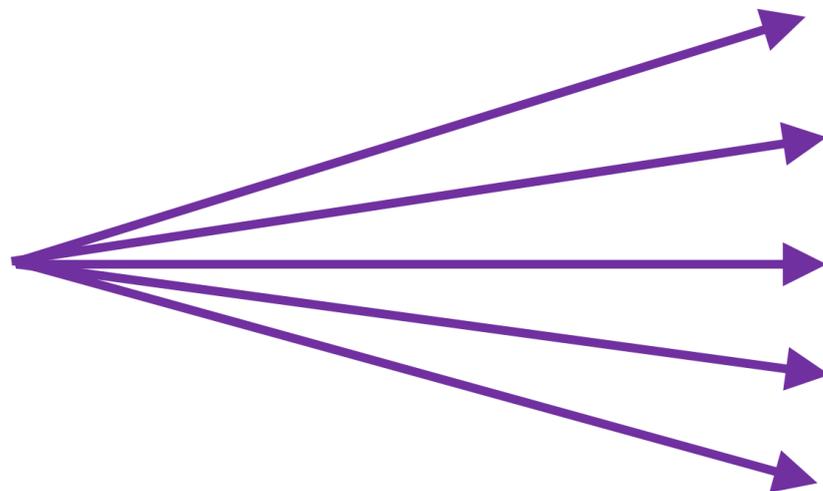
Plane waves



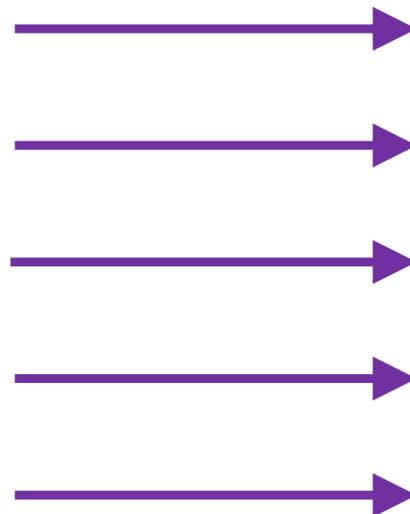
# RAY BUNDLES OF LIGHT

- Rays go **straight** in **homogeneous medium**
- **Ray bundles** represent an angular portion of spherical waves (diverging or converging)
- Ray bundles of interest:

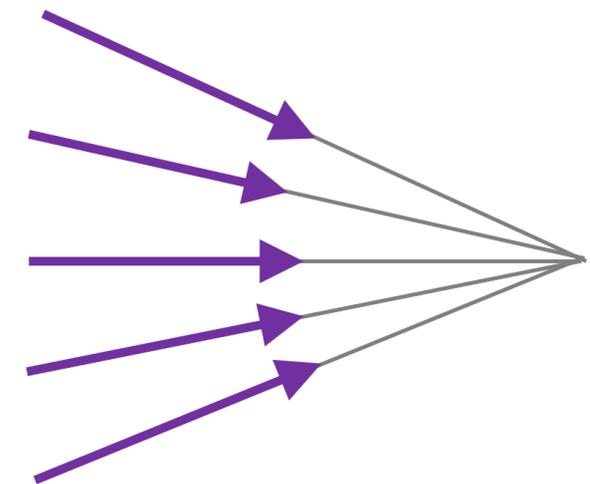
Rays from a  
**point source**



Parallel rays  
**(Collimation)**

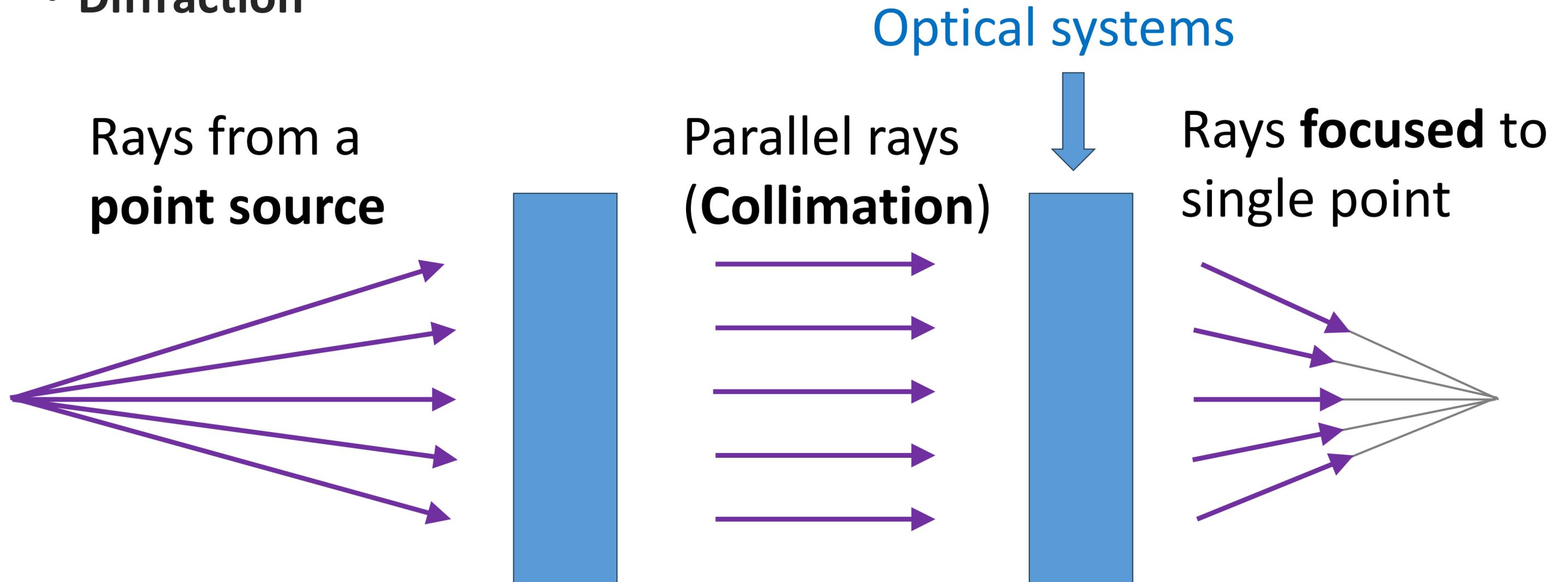


Rays **focused** to  
single point



# COLLIMATION & FOCUSING

- Changing the direction of light rays
  - **Heterogeneous medium: Gradient Index (GRIND)**
  - **Refraction, reflection**
  - **Diffraction**



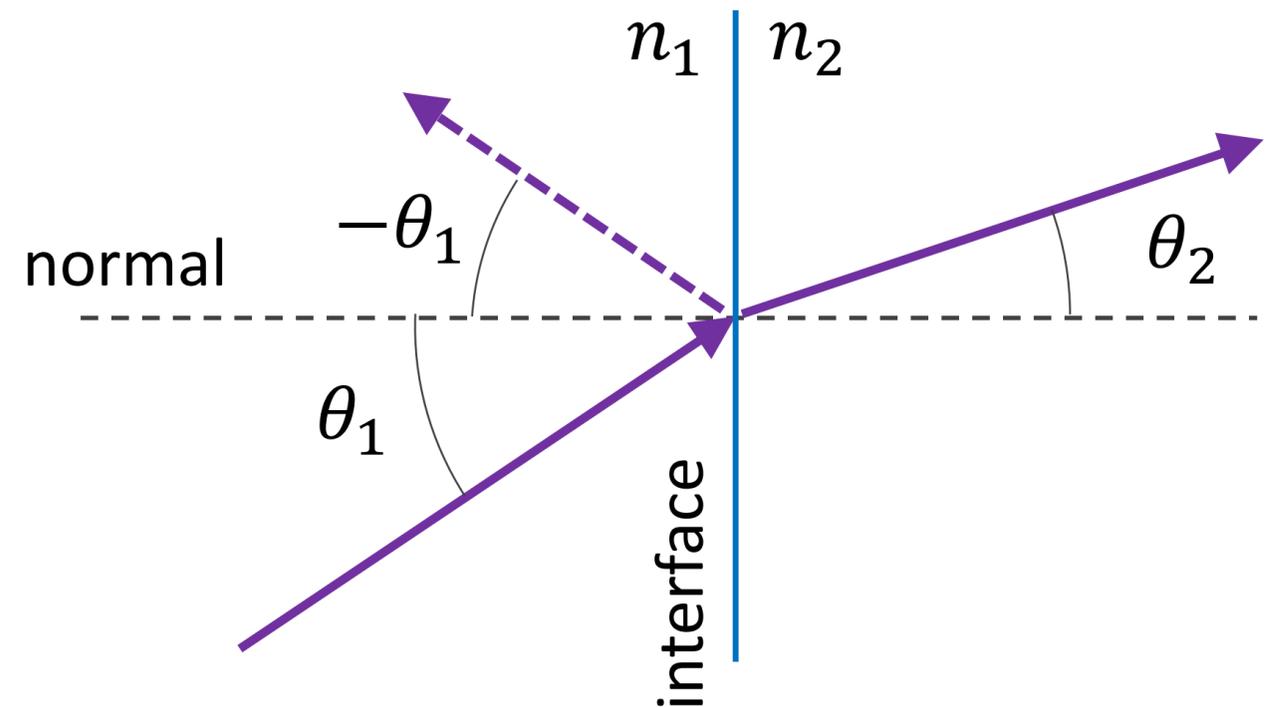
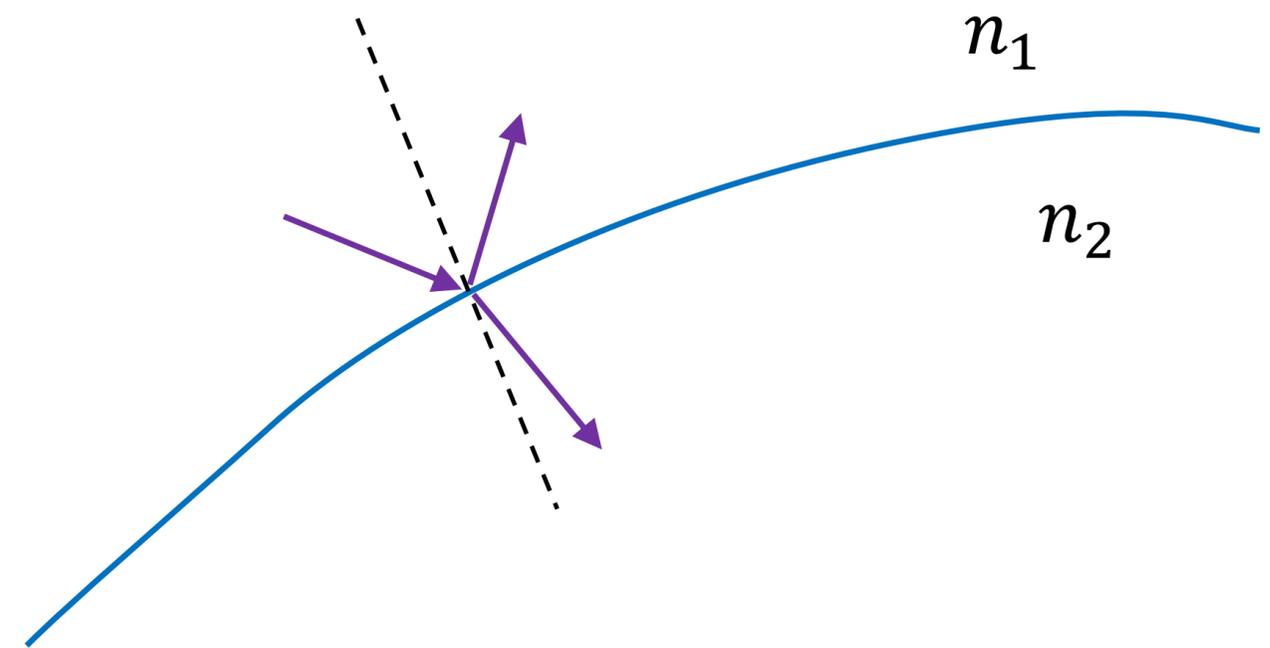
# REFRACTION OF RAYS AT SURFACE

- Wavelength  $\ll$  curvature radius

$$\lambda \ll R_c$$

- Refraction: Snell's law

$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$$

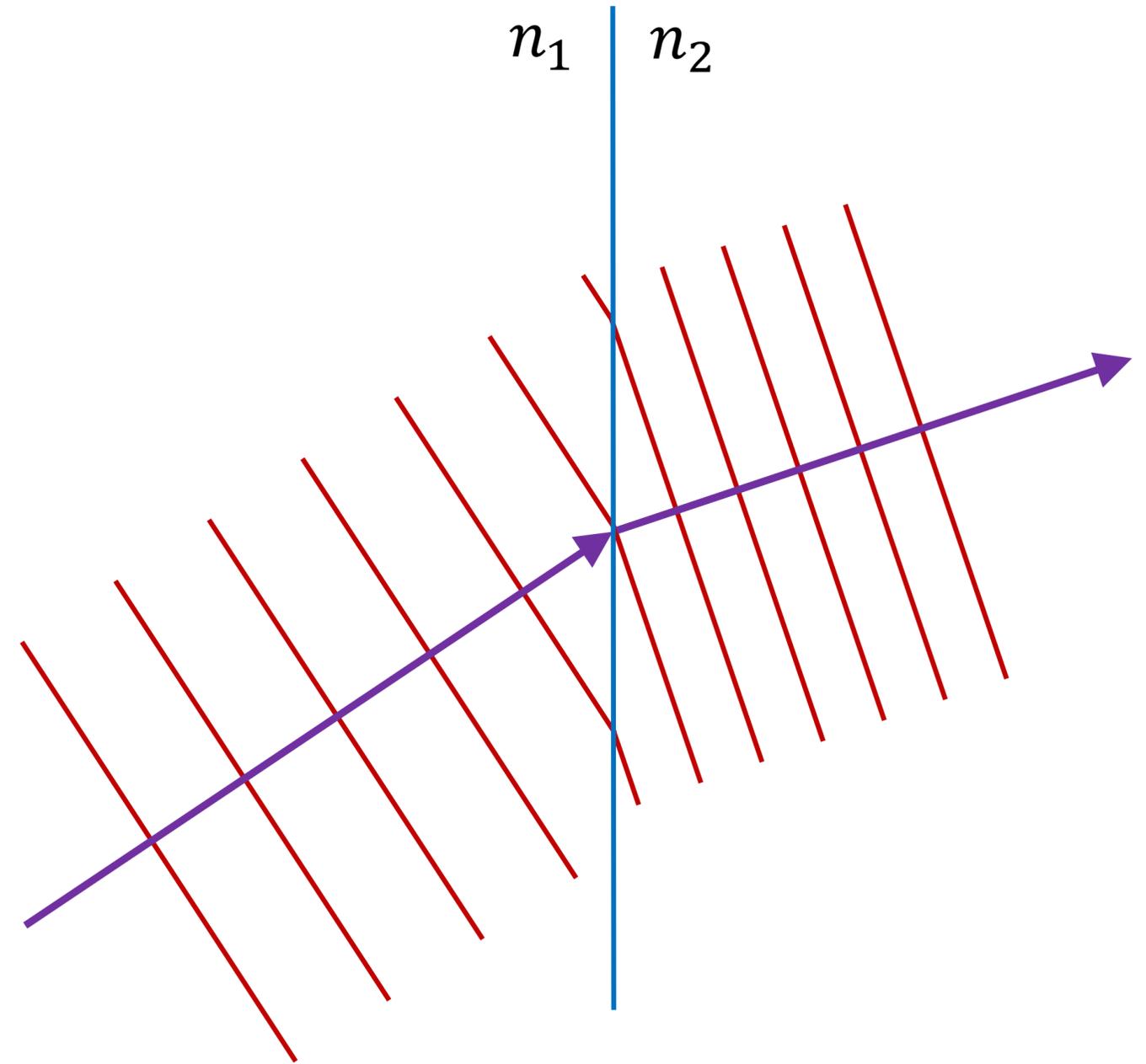


# FERMAT'S PRINCIPLE & WAVE FRONTS

- Phase along rays:  $\varphi(\mathbf{r}) = \mathbf{k} \cdot \mathbf{r}$

- Matching wave fronts

$$n_j = \frac{c_0}{v_j} = \frac{\text{velocity vacuum}}{\text{velocity medium}}$$



# FERMAT'S PRINCIPLE & WAVE FRONTS

- Phase along rays:

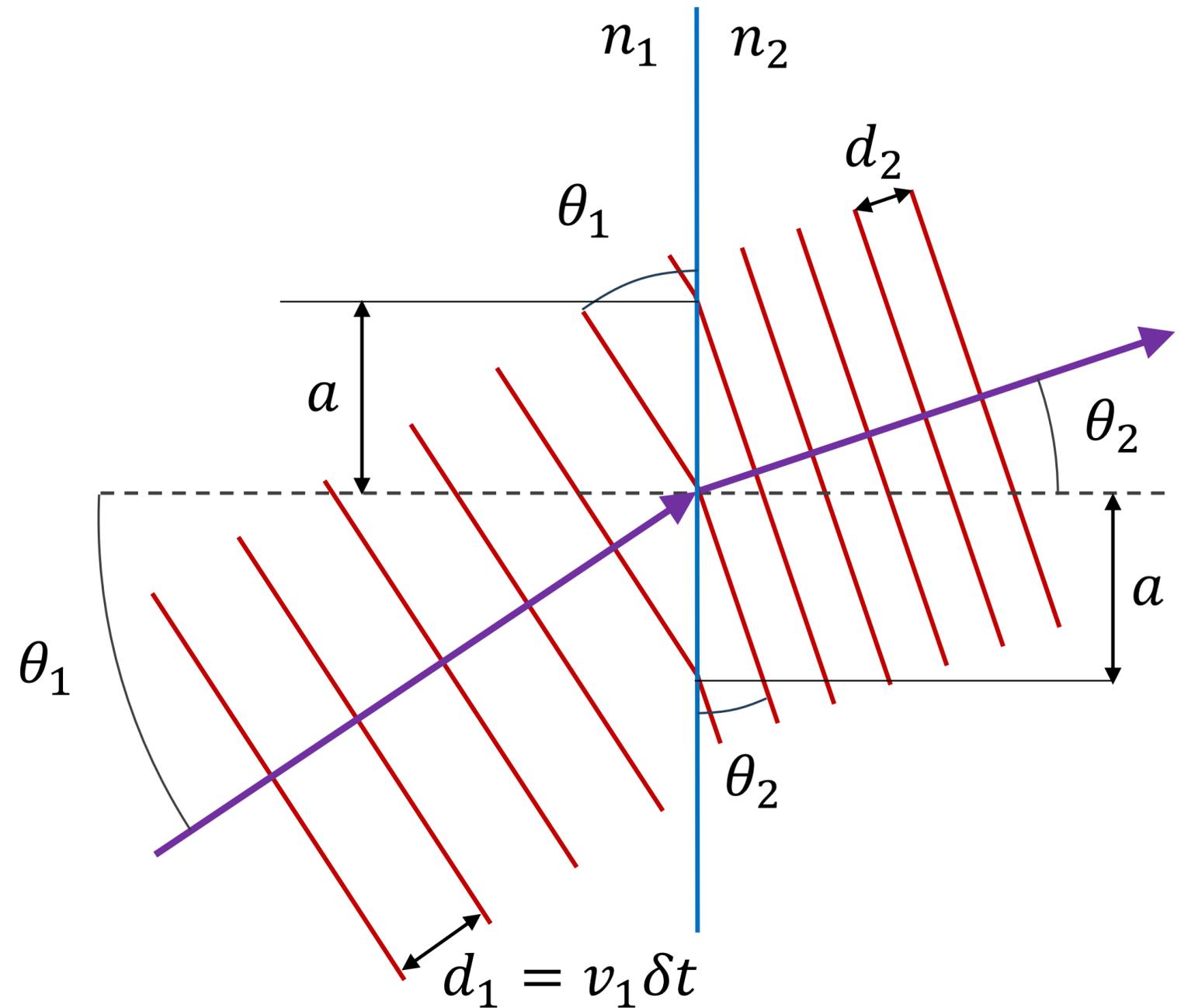
$$\varphi(\mathbf{r}) = \mathbf{k} \cdot \mathbf{r}$$

- Matching wave fronts

$$n_j = \frac{c_0}{v_j} = \frac{\text{velocity vacuum}}{\text{velocity medium}}$$

$$a = \frac{d_1}{\sin \theta_1} = \frac{v_1 \delta t}{\sin \theta_1} = \frac{c_0 \delta t}{n_1 \sin \theta_1}$$

$$a = \frac{d_2}{\sin \theta_2} = \frac{v_2 \delta t}{\sin \theta_2} = \frac{c_0 \delta t}{n_2 \sin \theta_2}$$



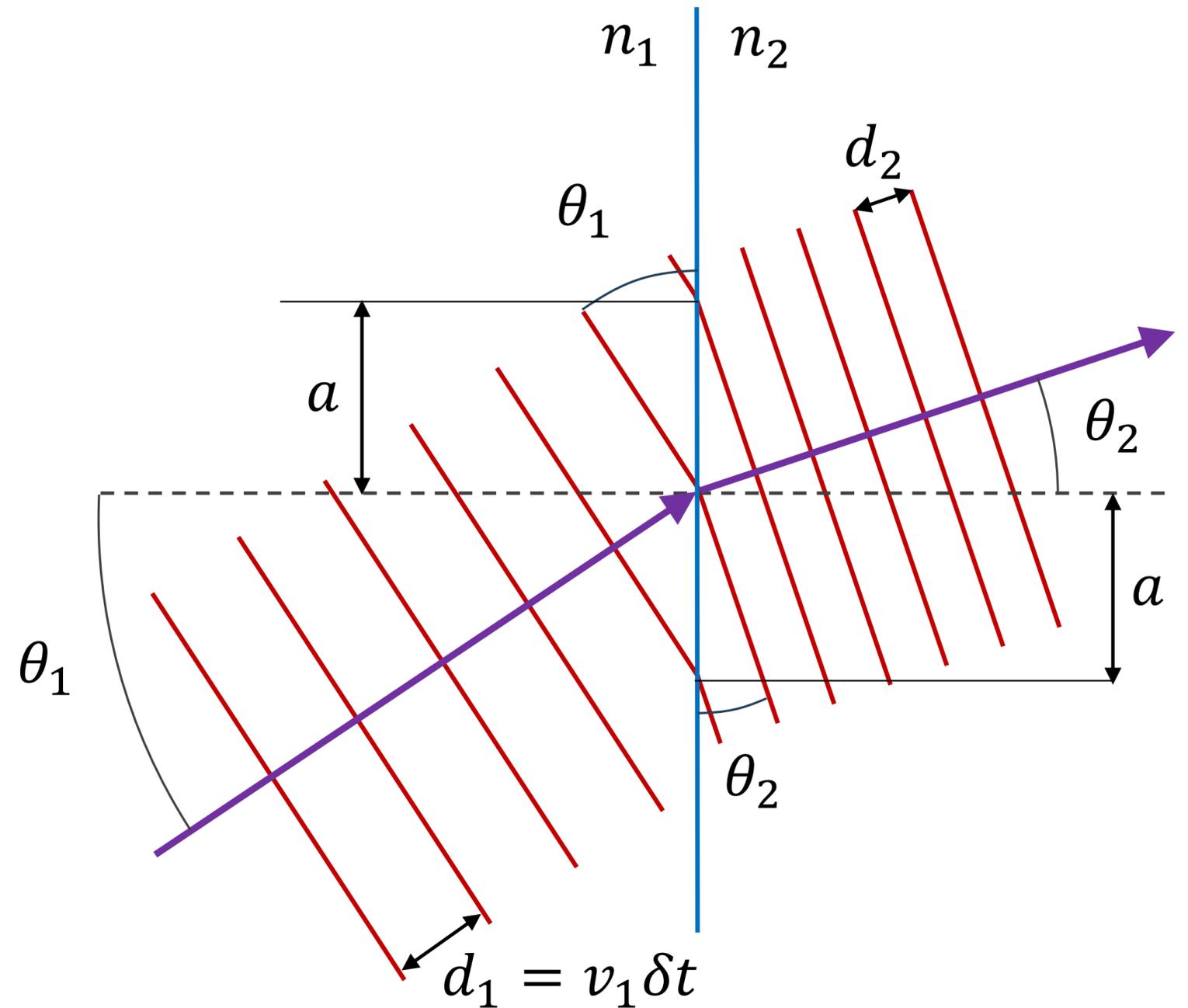
# FERMAT'S PRINCIPLE & WAVE FRONTS

- Phase along rays:  $\varphi(\mathbf{r}) = \mathbf{k} \cdot \mathbf{r}$

- Matching wave fronts

➔ 
$$\frac{c_0 \delta t}{n_1 \sin \theta_1} = \frac{c_0 \delta t}{n_2 \sin \theta_2}$$

➔ 
$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$$



# FERMAT'S PRINCIPLE & WAVE FRONTS

- **Fermat's principle**

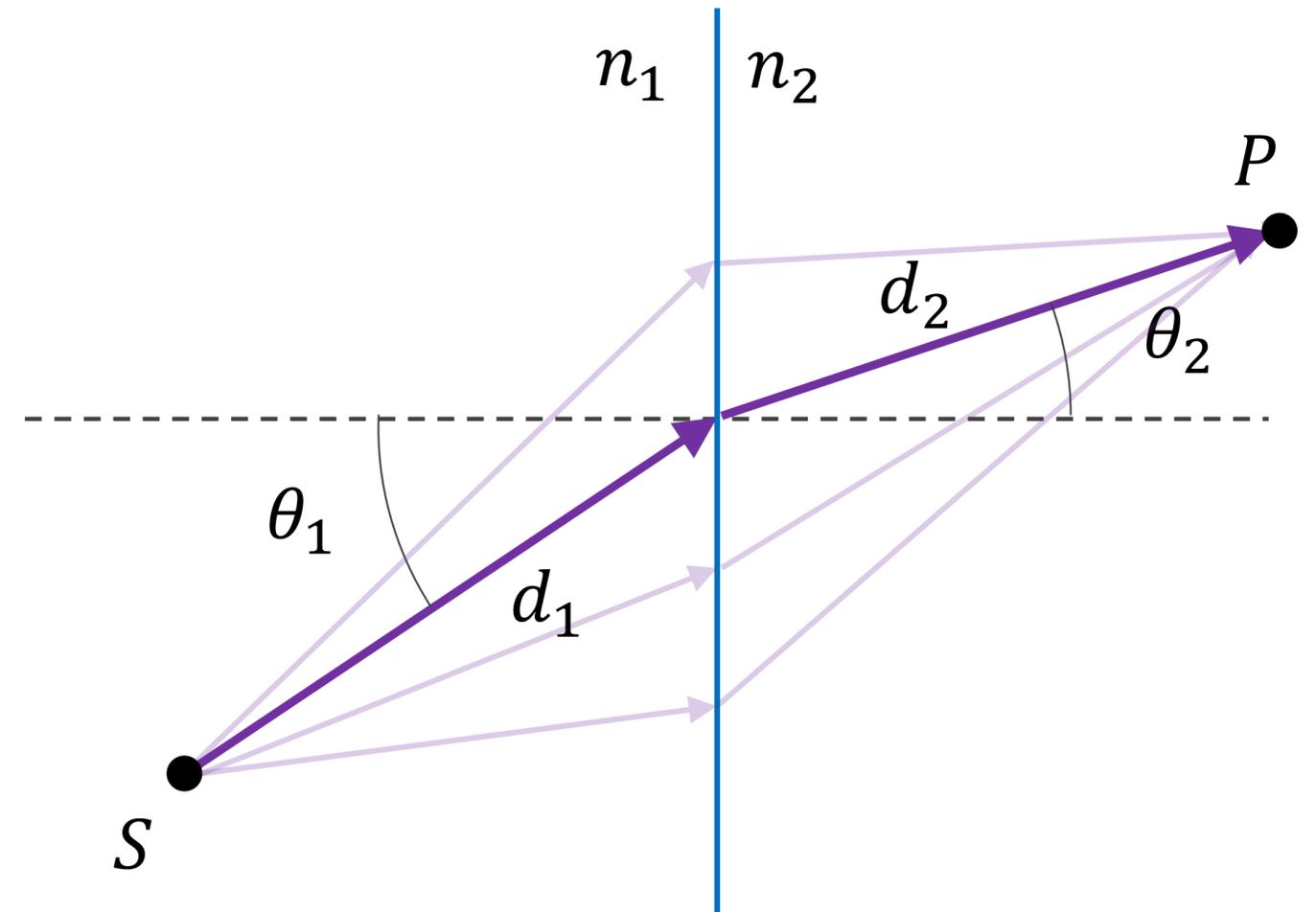
Light takes path of least time

Minimize time  $\Delta t$  :

$$\Delta t = \Delta t_1 + \Delta t_2 = \frac{d_1}{v_1} + \frac{d_2}{v_2}$$

Condition:

$$\frac{\partial \Delta t}{\partial z_1} = 0$$



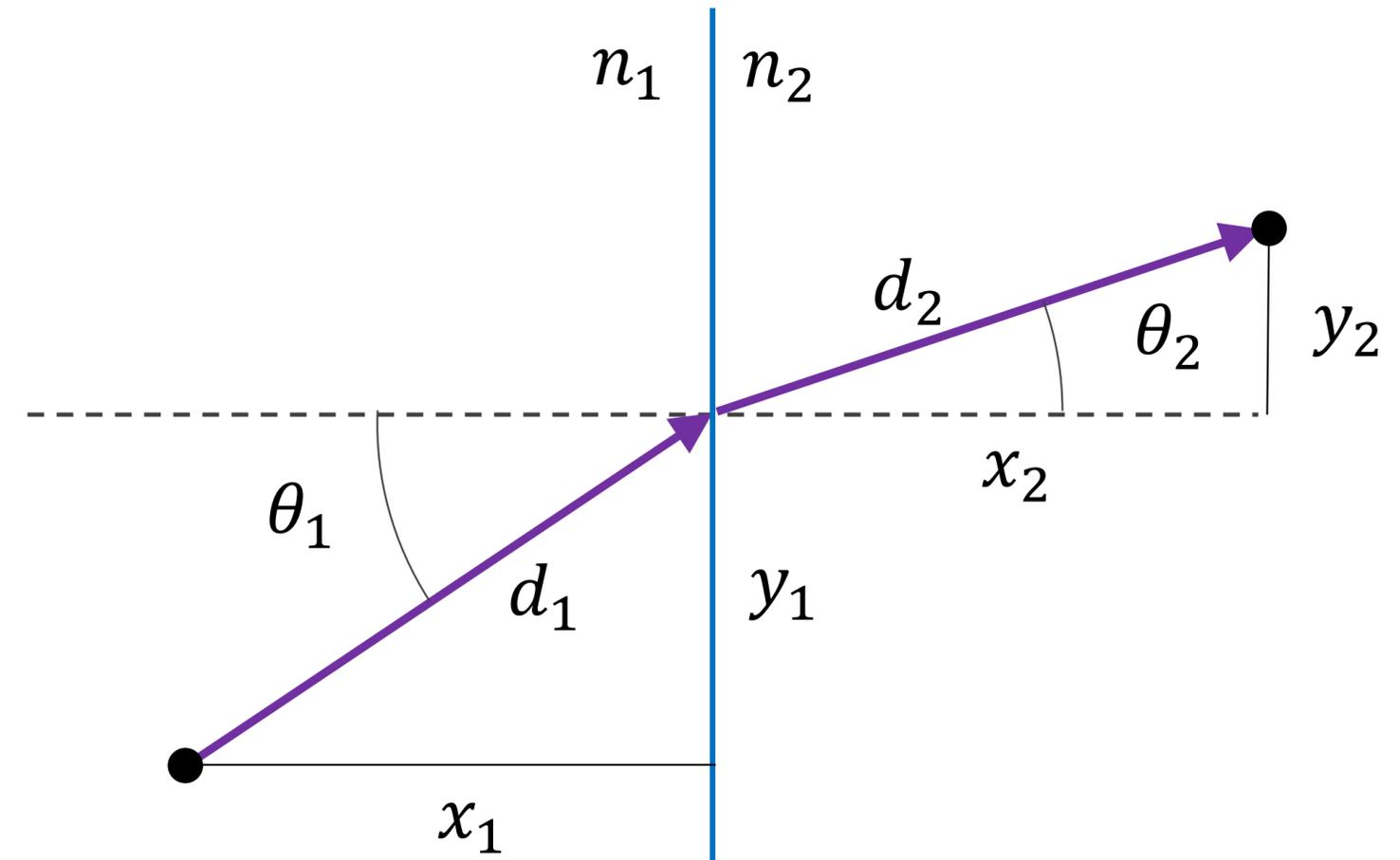
# FERMAT'S PRINCIPLE & WAVE FRONTS

- **Fermat's principle**  
Light takes path of least time

Minimize time  $\Delta t$  :

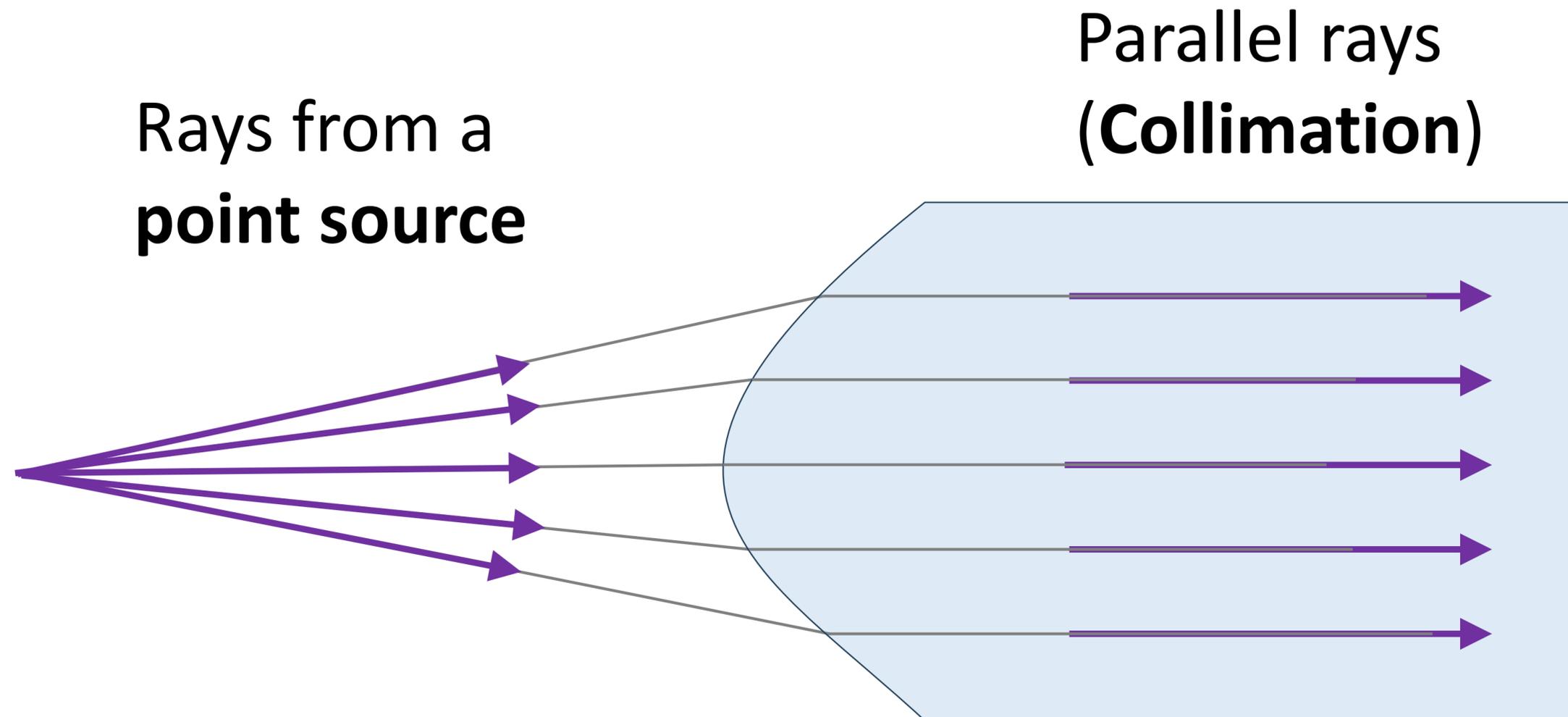
$$\begin{aligned}\Delta t &= \Delta t_1 + \Delta t_2 = \frac{d_1}{v_1} + \frac{d_2}{v_2} \\ &= \frac{\sqrt{x_1^2 + y_1^2}}{v_1} + \frac{\sqrt{x_2^2 + (y - y_1)^2}}{v_2}\end{aligned}$$

$$\frac{\partial \Delta t}{\partial y_1} = 0 \quad \Rightarrow \quad \frac{2y_1}{v_1 \sqrt{x_1^2 + y_1^2}} = \frac{2(y - y_1)}{v_2 \sqrt{x_2^2 + (y - y_1)^2}} \quad \Rightarrow \quad n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$$



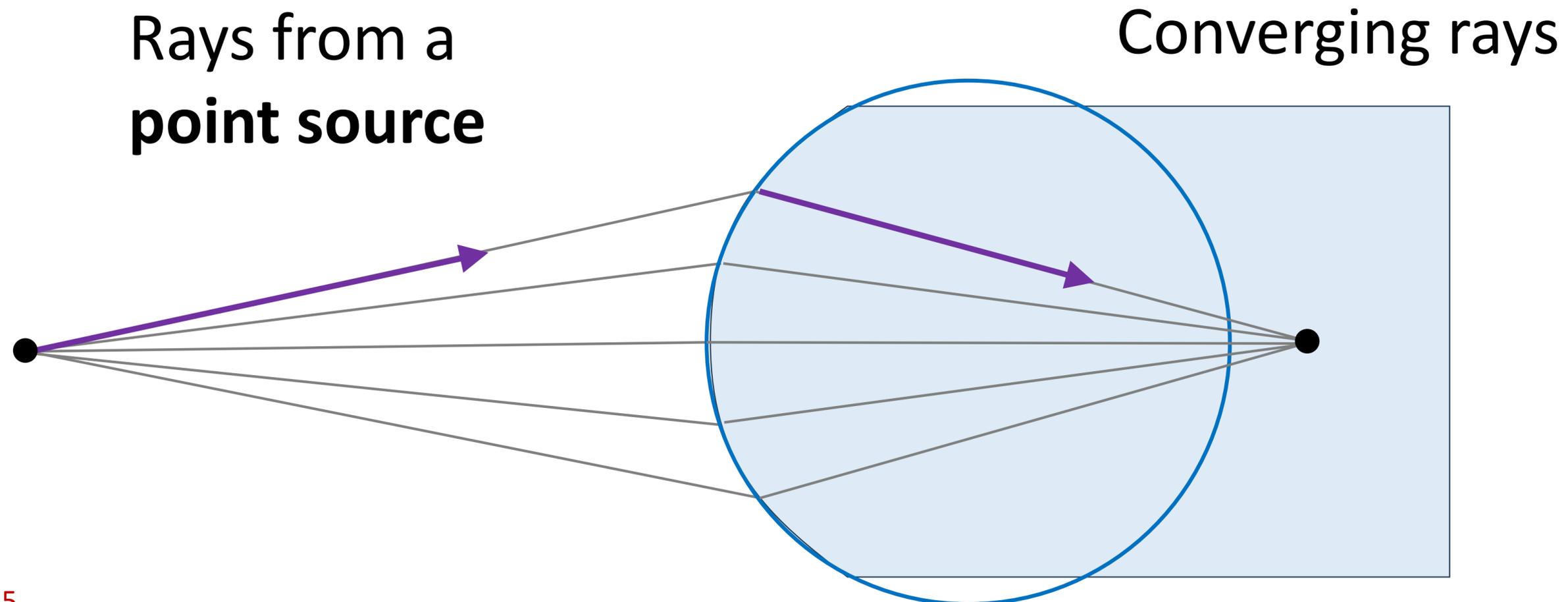
# REFRACTION: STIGMATIC SURFACES

- Changing the direction of light rays
- Perfect surface? Conic surfaces
- Example: Diverging rays (point source) to collimation



# REFRACTION: SPHERICAL SURFACES

- Not perfect
- Easier to produce
- Good performance for paraxial rays





# ZEMAX Practical session

# ZEMAX: SETTING UP

Start ZEMAX

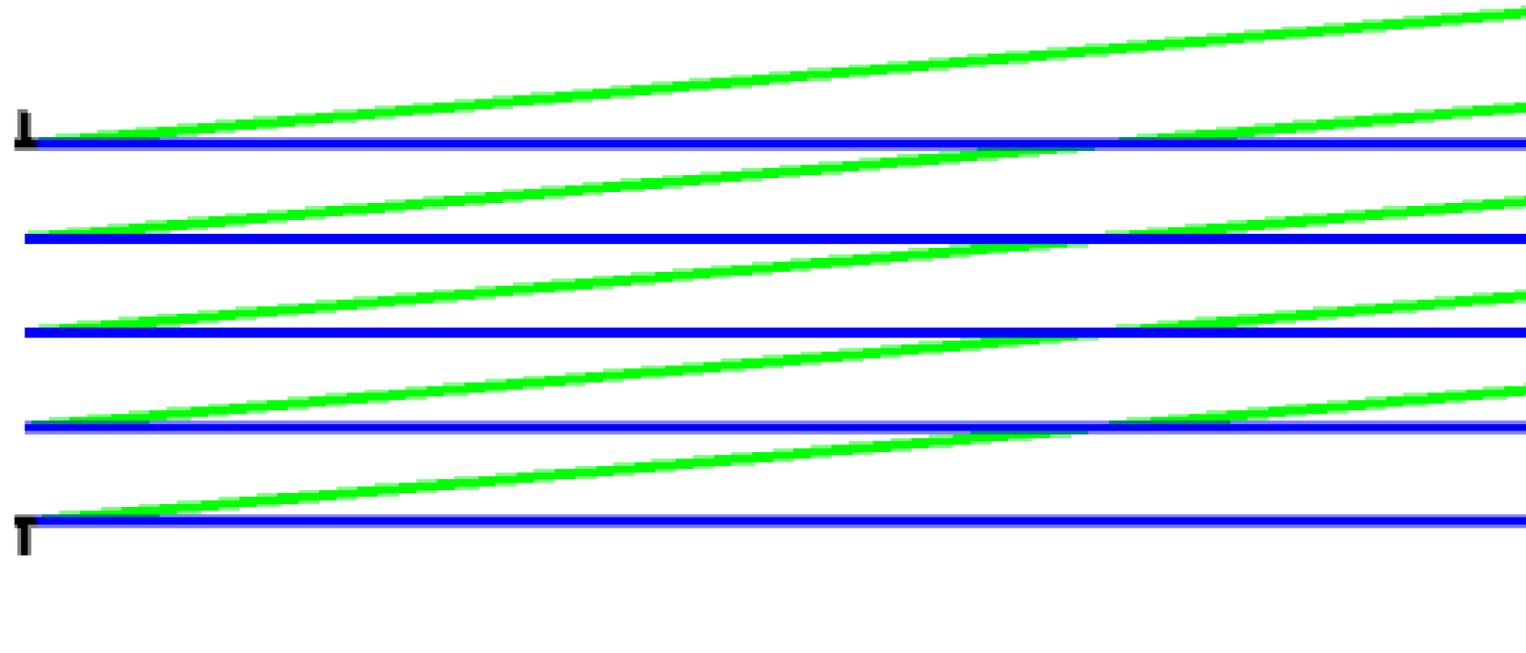
Save your file

Open convenient tabs:

1. System Explorer
2. Lens Data
3. Field Data Editor
4. Wavelength Data
5. Layout

# ZEMAX: INCOMING LIGHT

1. Set the **Aperture Value** to **25** in the **System Explorer**
2. Add one more row nonzero angle in the **Field Data Editor**
3. Change the **thickness** of the **STOP** to **100** in the **Lens Data** tab
4. **Settings** of the **Layout** tab: adapt the **Number Of Rays** to 5



System Explorer

Update: All Windows

Aperture

Aperture Type:

Entrance Pupil Diameter

Aperture Value:

25.0

Apodization Type:

Uniform

Clear Semi Diameter Margin Millimeters:

0.0

Clear Semi Diameter Margin %

0.0

Global Coordinate Reference Surface

1

Telecentric Object Space

Afocal Image Space

Iterate Solves When Updating

Fast Semi-Diameters

Check GRIN Apertures

Wavelengths

Settings

Wavelength 1 (0.55 um, Weight = 1.00)

Add Wavelength

Fields

Environment

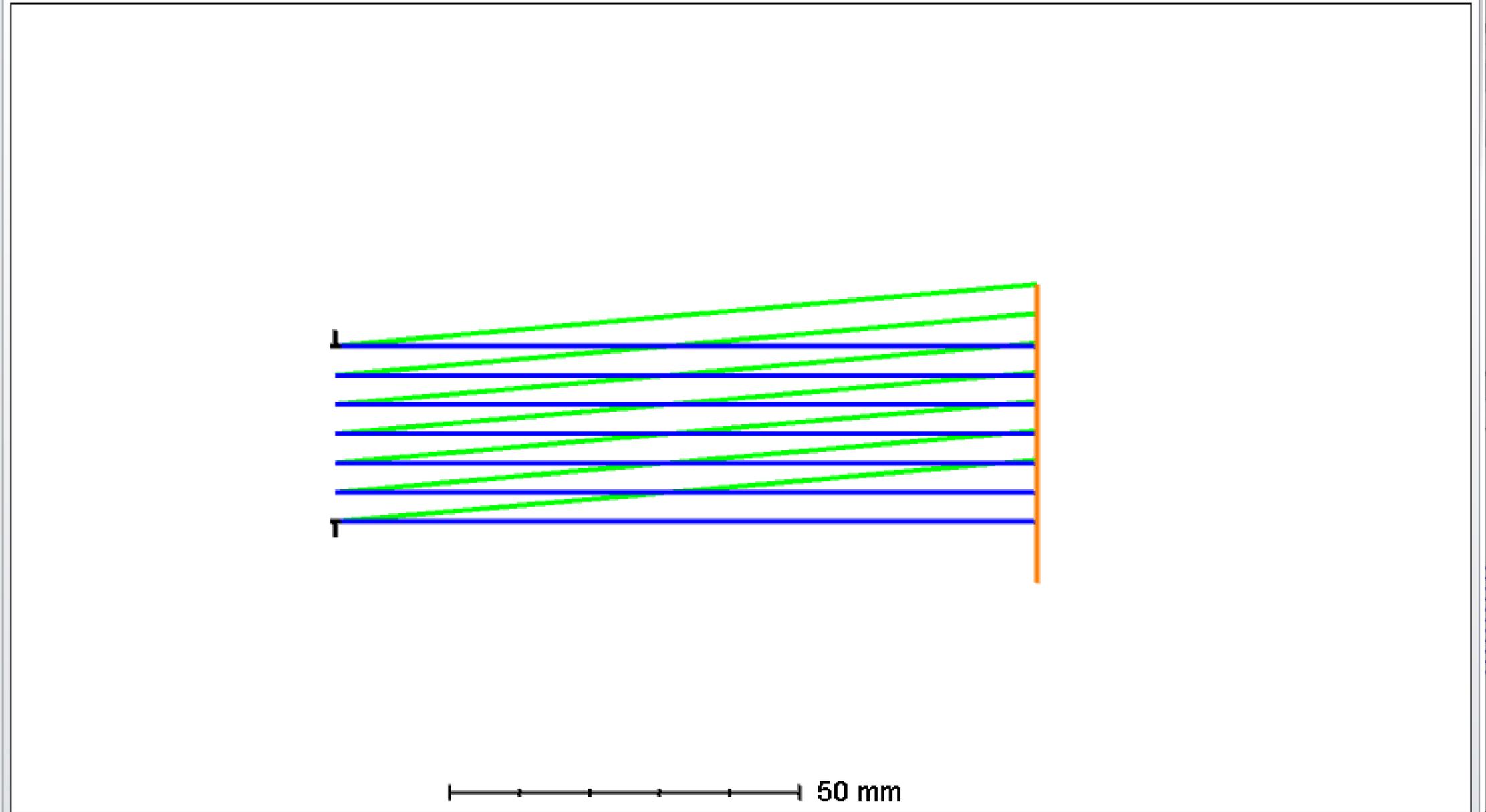
Polarization

Advanced

Ray Aiming

Material Catalogs

Title/Notes



Layout

10/11/2025  
Total Axial Length: 100.00000 mm

Zemax  
Ansys Zemax OpticStudio 2024 R1.00

Ex1\_incoming\_rays.zos  
Configuration 1 of 1

**System Explorer**

Update: All Windows ▾

- Aperture
  - Aperture Type: Entrance Pupil Diameter
  - Aperture Value: 25.0
  - Apodization Type: Uniform
  - Clear Semi Diameter Margin Millimeters: 0.0
  - Clear Semi Diameter Margin %: 0.0
  - Global Coordinate Reference Surface: 1
  - Telecentric Object Space
  - Afocal Image Space
  - Iterate Solves When Updating
  - Fast Semi-Diameters
  - Check GRIN Apertures
- Wavelengths
  - Settings
  - Wavelength 1 (0.55 um, Weight = 1.00)
  - Add Wavelength
- Fields
- Environment
- Polarization
- Advanced
- Ray Aiming
- Material Catalogs
- Title/Notes

Update: All Windows ▾

**Field Type**

Fields Wizard

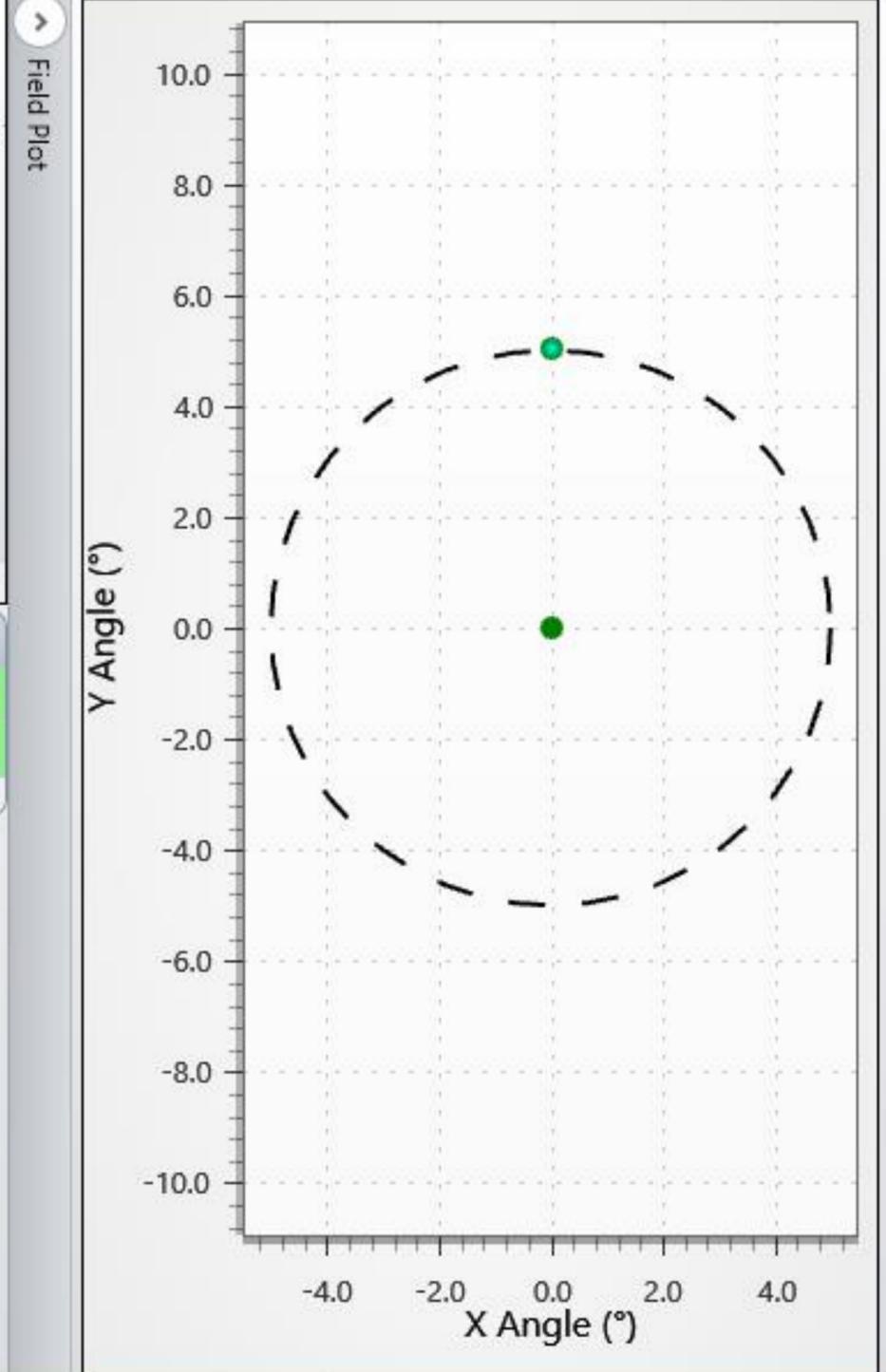
Current Field (2)

Type: Angle in degrees

Normalization: Radial Normalized by: 5

Convert To: Select a field type...

	Comment	X Angle (°)	Y Angle (°)	Weight	VDX
1		0.000	0.000	1.000	0.000
2		0.000	5.000	1.000	0.000



Update: All Windows

Aperture

Aperture Type: Entrance Pupil Diameter

Aperture Value: 25.0

Apodization Type: Uniform

Clear Semi Diameter Margin Millimeters: 0.0

Clear Semi Diameter Margin %: 0.0

Global Coordinate Reference Surface: 1

Telecentric Object Space

Afocal Image Space

Iterate Solves When Updating

Fast Semi-Diameters

Check GRIN Apertures

Wavelengths

- Settings
- Wavelength 1 (0.55 um, Weight = 1.00)
- Add Wavelength

Fields

Environment

Polarization

Advanced

Ray Aiming

Material Catalogs

Title/Notes

Settings

Line Thickness

First Surface: 1

Last Surface: 2

Number Of Rays: 5

Scale Bar: On

Y Stretch: 1

Suppress Frame

Fletch Rays

Wavelength: 1

Field: All

Color Rays By: Field #

Upper Pupil: 1

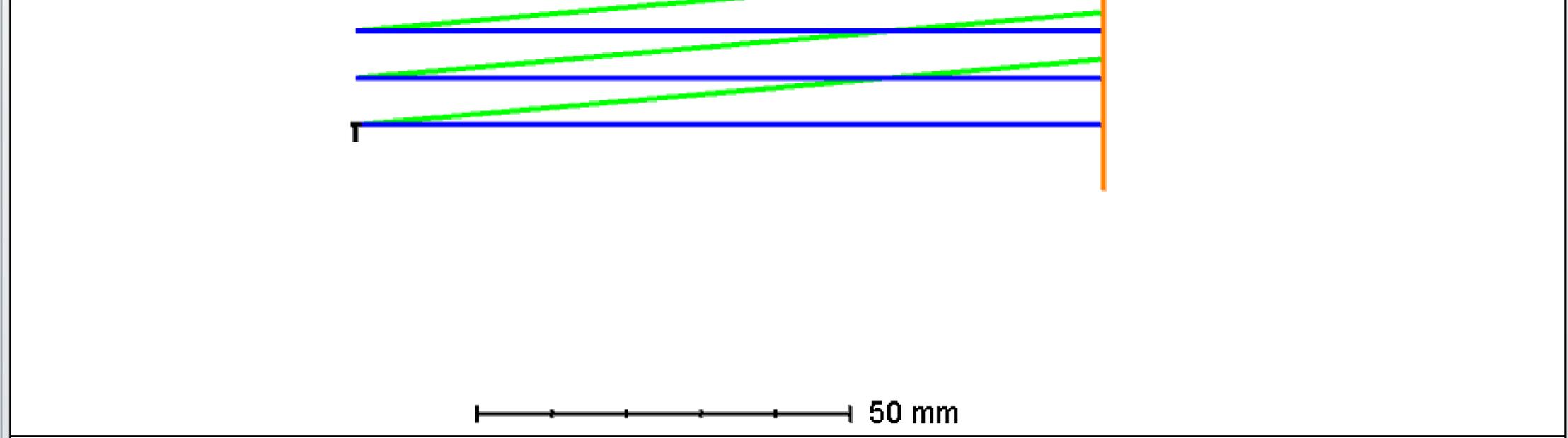
Lower Pupil: -1

Delete Vignetted

Marginal And Chief Only

Auto Apply

Apply OK Cancel Save Load Reset



Layout

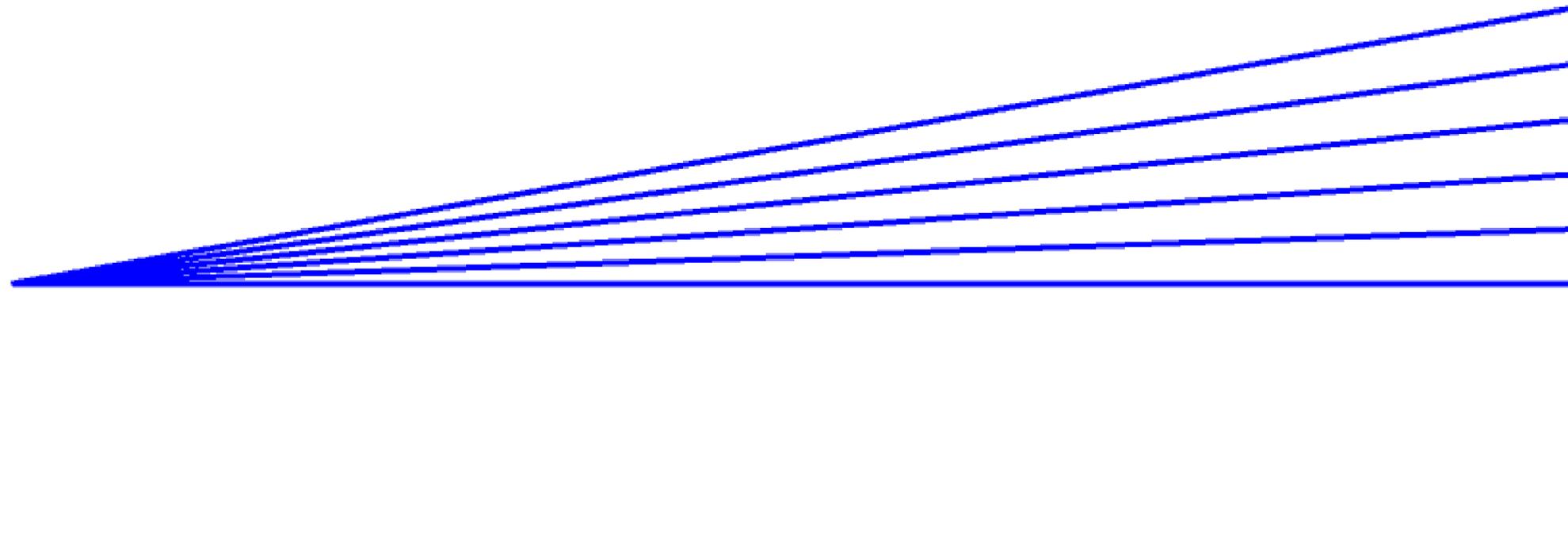
10/11/2025  
 Total Axial Length: 100.00000 mm

Zemax  
 Ansys Zemax OpticStudio 2024 R1.00

Ex1\_incoming\_rays.zos  
 Configuration 1 of 1

# ZEMAX: A POINT SOURCE

1. Reduce the **Aperture Value** in the **System Explorer** to **0.01**
2. Adjust the **OBJECT thickness** in the **Lens Data** tab
3. Add more rows with increasing angles in the **Field Data Editor**
4. In the **Settings** of the **Layout** tab: reduce **Number Of Rays** to **1**, and **Color Rays By** to **Wave #**



System Explorer ?

Update: All Windows ▾

Aperture

Aperture Type:

Entrance Pupil Diameter ▾

Aperture Value:

0.01

Apodization Type:

Uniform ▾

Clear Semi Diameter Margin Millimeters:

0.0

Clear Semi Diameter Margin %

0.0

Global Coordinate Reference Surface

1 ▾

Telecentric Object Space

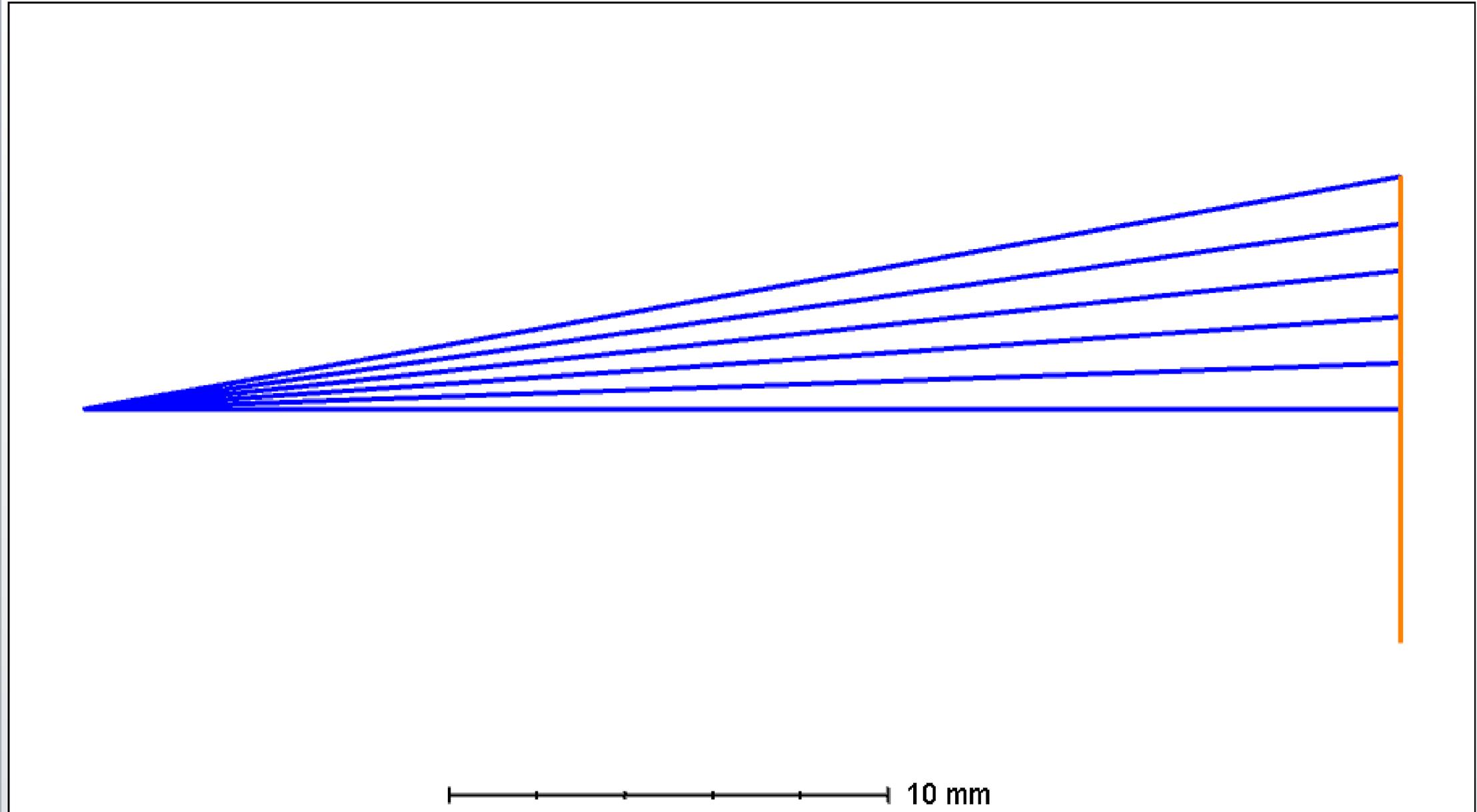
Afocal Image Space

Iterate Solves When Updating

Fast Semi-Diameters

Check GRIN Apertures

- ▶ Fields
- ▶ Wavelengths
- ▶ Environment
- ▶ Polarization
- ▶ Advanced
- ▶ Ray Aiming
- ▶ Material Catalogs
- ▶ Title/Notes
- ▶ Files
- ▶ Units
- ▶ Cost Estimator



Layout

10/11/2025  
Total Axial Length: 30.00000 mm

IYTE  
Ansys Zemax OpticStudio 2024 R1.00

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Ex2\_point\_source.zos  
Configuration 1 of 1

Update: All Windows

Aperture

Aperture Type:

Entrance Pupil Diameter

Aperture Value:

0.01

Apodization Type:

Uniform

Clear Semi Diameter Margin Millimeters:

0.0

Clear Semi Diameter Margin %

0.0

Global Coordinate Reference Surface

1

- Telecentric Object Space
- Afocal Image Space
- Iterate Solves When Updating
- Fast Semi-Diameters
- Check GRIN Apertures

- ▶ Fields
- ▶ Wavelengths
- ▶ Environment
- ▶ Polarization
- ▶ Advanced
- ▶ Ray Aiming
- ▶ Material Catalogs
- ▶ Title/Notes
- ▶ Files
- ▶ Units
- ▶ Cost Estimator

Update: All Windows

Field 6 Properties Configuration 1/1 Field Type: Angle

Field Type

Fields Wizard

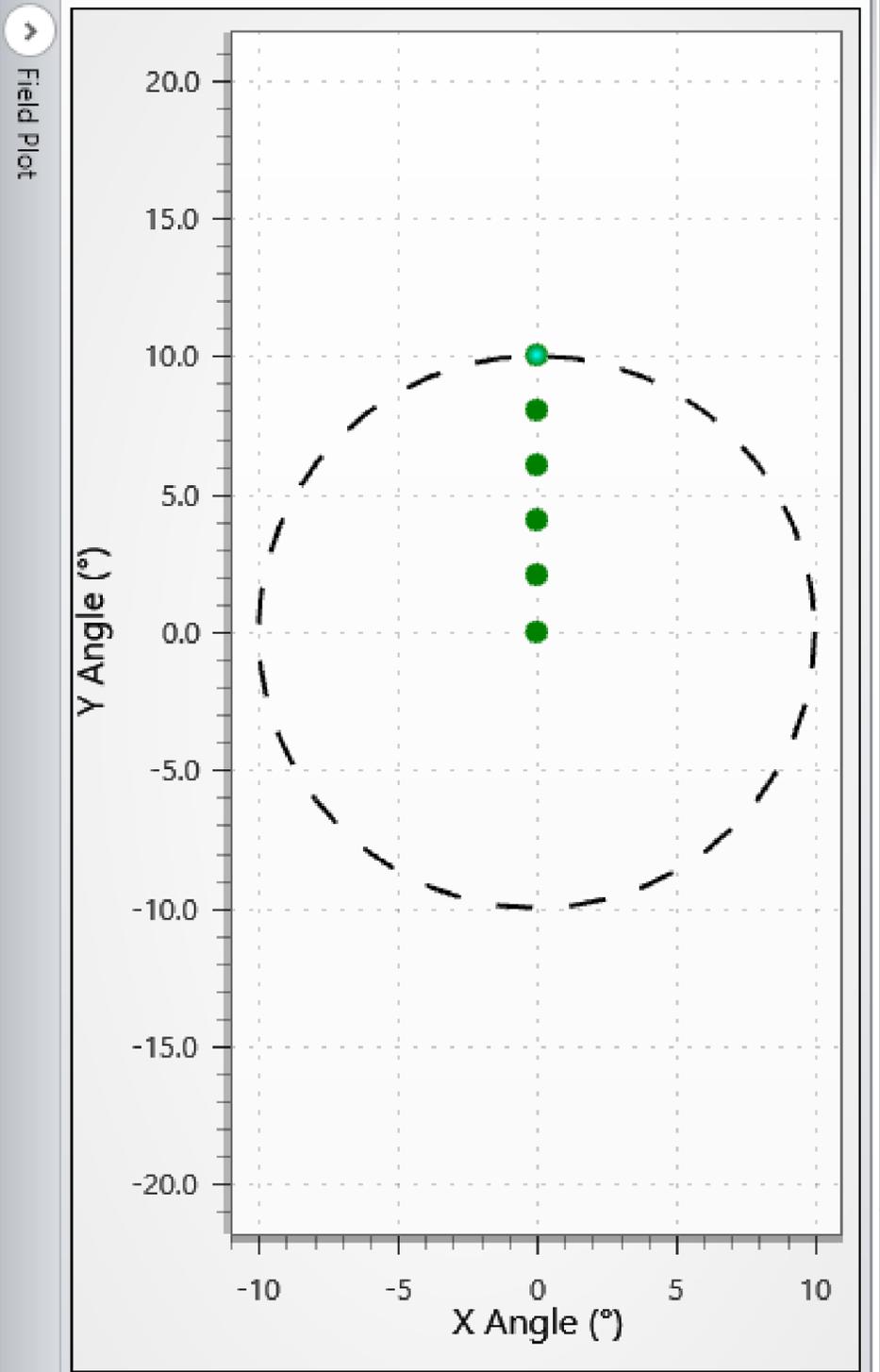
Current Field (6)

Type: Angle in degrees

Normalization: Radial Normalized by: 10

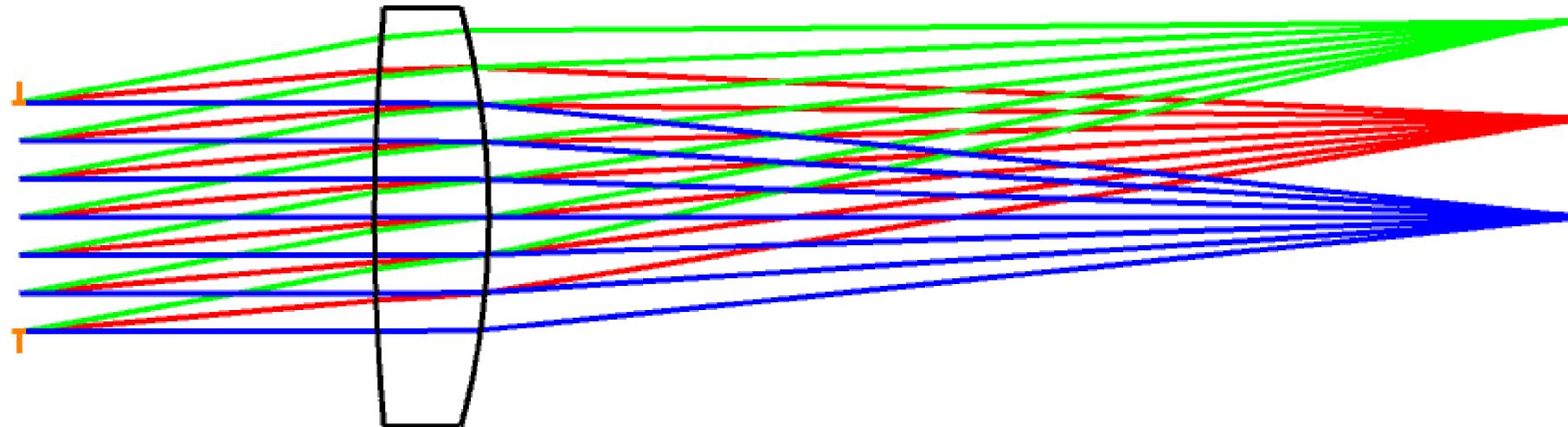
Convert To: Select a field type...

	Comment	X Angle (°)	Y Angle (°)	Weight	VDX
1		0.000	0.000	1.000	0.000
2		0.000	2.000	1.000	0.000
3		0.000	4.000	1.000	0.000
4		0.000	6.000	1.000	0.000
5		0.000	8.000	1.000	0.000
6		0.000	10.000	1.000	0.000



# ZEMAX: A FIRST LENS SYSTEM

1. Set the **Aperture Value** to 10 in the **System Explorer**
2. Clear **Semi Aperture Margin** to 1 in the **System Explorer - Aperture**
3. Three angles in the **Field Data Editor**: e.g. 0, 5, 10 degrees
4. **Lens Data** tab: See values next slide
5. Apply **Optimize – Quick Focus**



System Explorer

Update: All Windows

Aperture

Aperture Type:

Entrance Pupil Diameter

Aperture Value:

10.0

Apodization Type:

Uniform

Clear Semi Diameter Margin Millimeters:

1.0

Clear Semi Diameter Margin %

0.0

Global Coordinate Reference Surface

2

Telecentric Object Space

Afocal Image Space

Iterate Solves When Updating

Fast Semi-Diameters

Check GRIN Apertures

- ▶ Fields
- ▶ Wavelengths
- ▶ Environment
- ▶ Polarization
- ▶ Advanced
- ▶ Ray Aiming
- ▶ Material Catalogs
- ▶ Title/Notes
- ▶ Files
- ▶ Units
- ▶ Cost Estimator

Lens Data Field Data Editor

Update: All Windows

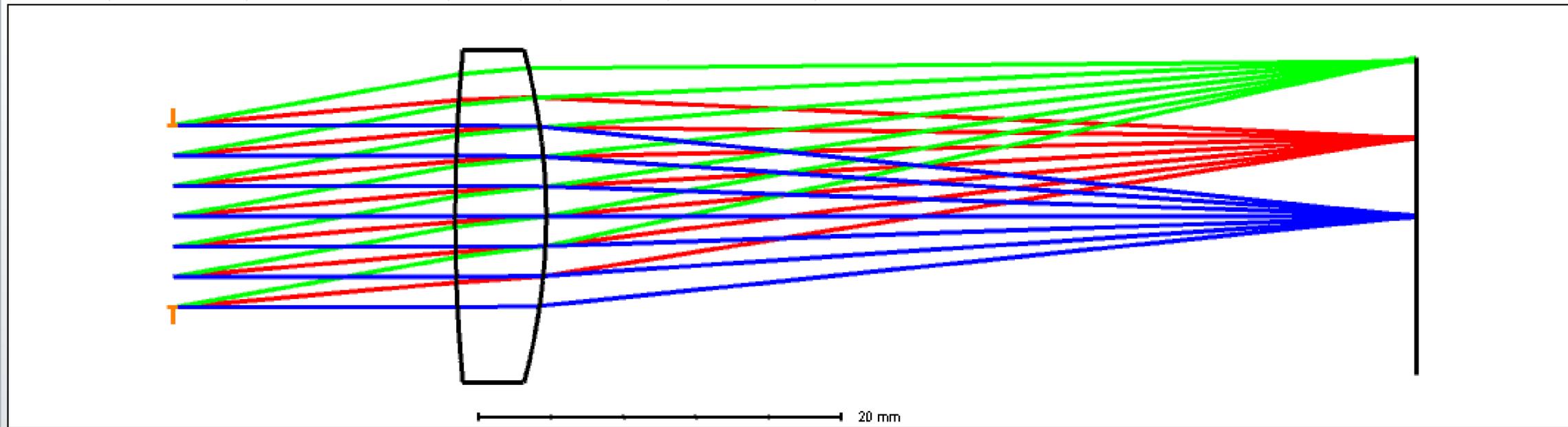
Surface 2 Properties

Configuration 1/1

	Surface Type	Comment	Radius	Thickness	Material	Coating	Clear Semi-Dia	Chip Zone	Mech Semi-Dia	Conic	TCE x 1E-6
0	OBJECT	Standard	Infinity	Infinity			Infinity	0.000	Infinity	0.0...	0.000
1		Standard	Infinity	0.000			0.000 U	0.000	0.000	0.0...	0.000
2	STOP	Standard	Infinity	15.575 V			5.000 U	0.000	5.000	0.0...	0.000
3		Standard	front lens 98.000 V	5.000 V	N-BK7		8.801	0.000	9.125	0.0...	-
4		Standard	rear lens -34.638 F	47.950 V			9.125	0.000	9.125	0.0...	0.000
5	IMAGE	Standard	Infinity	-			8.705	0.000	8.705	0.0...	0.000

1: Layout

Settings

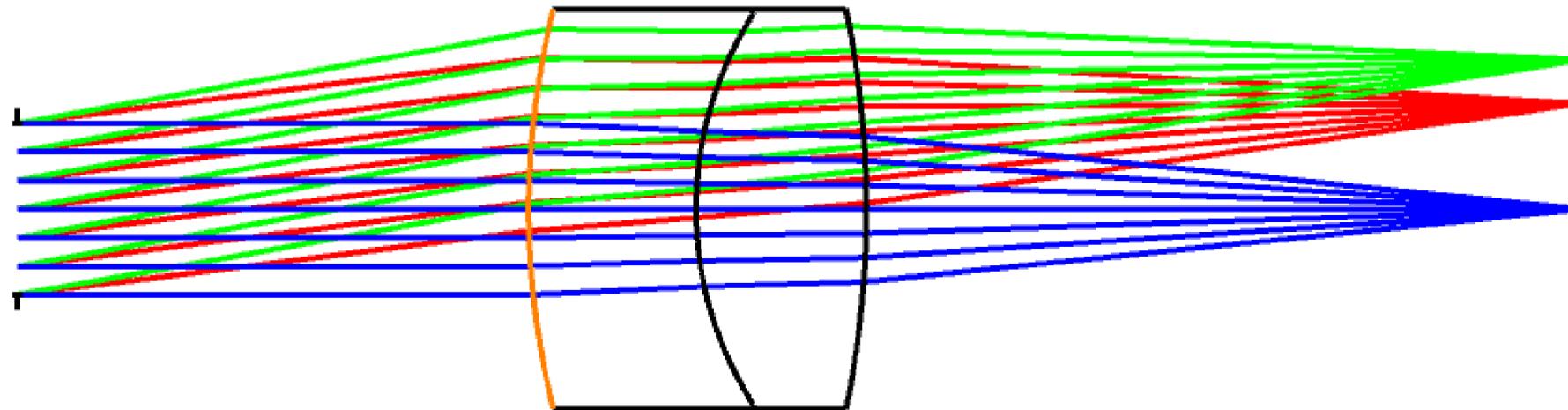


10/12/2025  
Total Axial Length: 68.52505 mm

Zemax  
Ansys Zemax OpticStudio 2024 R1.00  
Ex4\_doublet\_lens.zos  
Configuration 1 of 1

# ZEMAX: A FIRST LENS SYSTEM

1. Set the **Aperture Value** to 10 in the **System Explorer**
2. Clear **Semi Aperture Margin** to 1 in the **System Explorer - Aperture**
3. Three angles in the **Field Data Editor**: e.g. 0, 5, 10 degrees
4. **Lens Data** tab: See values next slide (take care of the materials)
5. Apply **Optimize – Quick Focus**



System Explorer

Update: All Windows ▾

Aperture

Aperture Type: Entrance Pupil Diameter ▾

Aperture Value: 10.0

Apodization Type: Uniform ▾

Clear Semi Diameter Margin Millimeters: 1.0

Clear Semi Diameter Margin %: 0.0

Global Coordinate Reference Surface: 2 ▾

Telecentric Object Space

Afocal Image Space

Iterate Solves When Updating

Fast Semi-Diameters

Check GRIN Apertures

Fields

Open Field Data Editor

- Settings
- Field 1 (X = 0.000, Y = 0.000, Weight = 1.000)
- Field 2 (X = 0.000, Y = 10.000, Weight = 1.000)
- Field 3 (X = 0.000, Y = 7.071, Weight = 1.000)
- Add Field
- Wavelengths
- Environment
- Polarization
- Advanced
- Ray Aiming
- Material Catalogs
- Title/Notes
- Files
- Units

Lens Data X Field Data Editor

Update: All Windows ▾

Surface 3 Properties < >

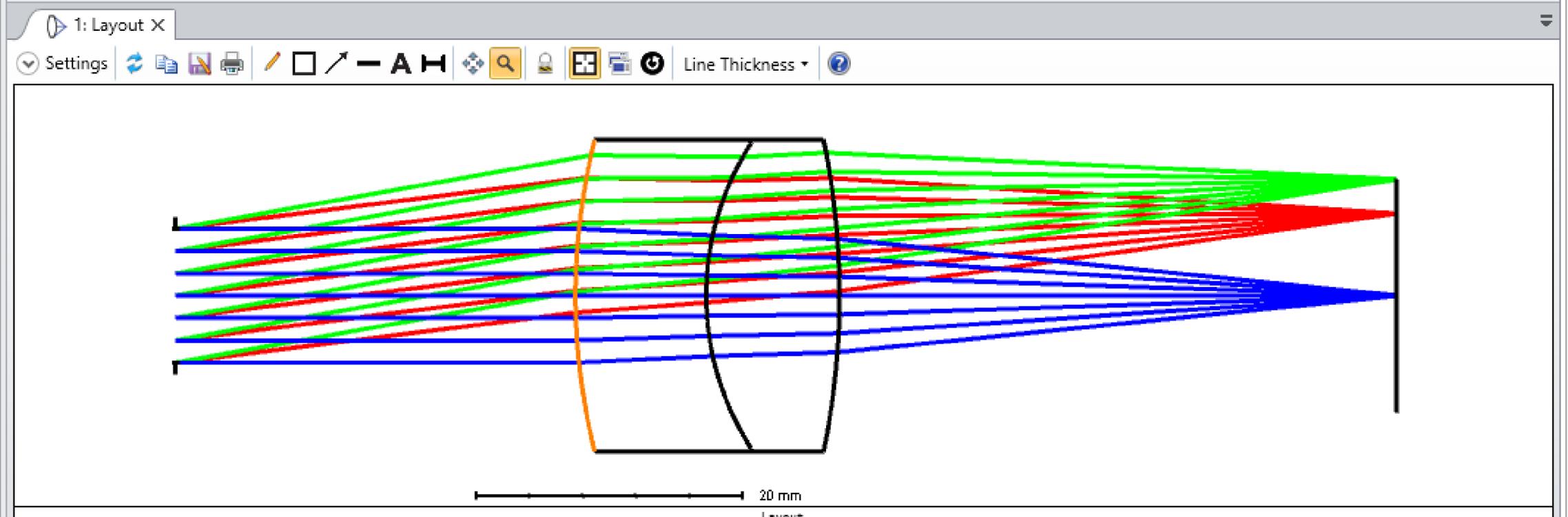
Configuration 1/1 < >

Surface	Type	Comment	Radius	Thickness	Material	Coating	Clear Semi-Dia	Chip Zone	Mech Semi-Dia	Conic	TCE x
0	OBJECT		Infinity	Infinity			Infinity	0.000	Infinity	0.0...	0.00
1			Infinity	5.000			0.000 U	0.000	0.000	0.0...	0.00
2	STOP		Infinity	30.000 V			5.000	0.000	5.000	0.0...	0.00
3		front lens	48.000 V	9.800 V	N-SF57 S		11.495	0.000	11.675	0.0...	
4		middle	21.000 V	10.000 V	N-BAF10 S		11.365	0.000	11.675	0.0...	
5		rear lens	-56.860 F	41.766 V			11.675	0.000	11.675	0.0...	0.00
6	IMAGE		Infinity	-			8.718	0.000	8.718	0.0...	0.00

1: Layout X

Settings

Line Thickness ▾

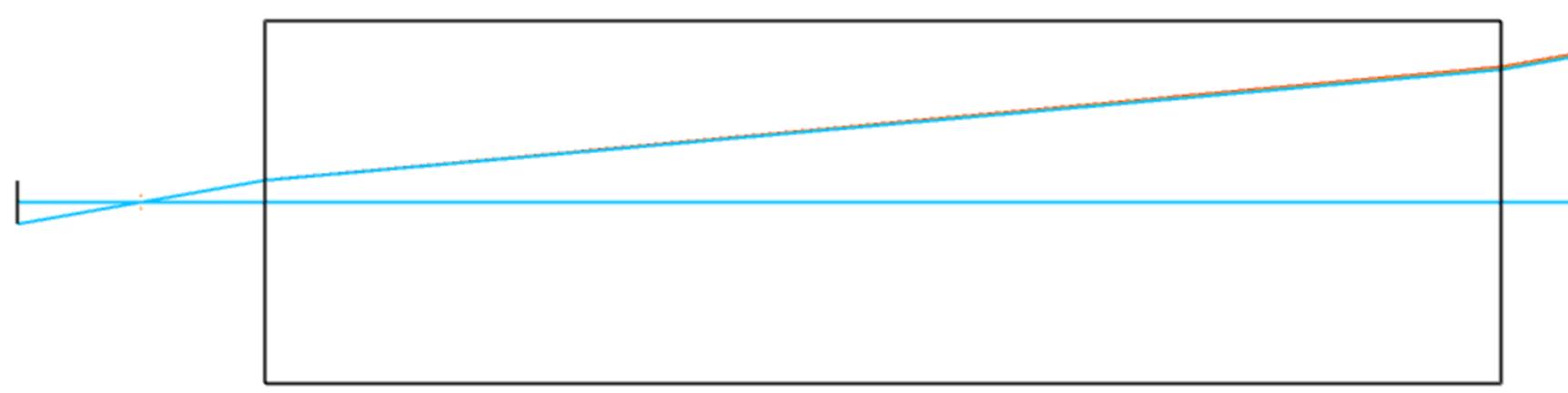


10/12/2025  
Total Axial Length: 91.56565 mm

Zemax  
Ansys Zemax OpticStudio 2024 R1.00  
Ex4\_doublet\_lens.zos  
Configuration 1 of 1

# ZEMAX: DIFFERENT WAVELENGTHS

1. Use a setup with two planar surfaces (a slab)
2. Add one nonzero angle in the **Field Data Editor**
3. Open the **wavelengths** tab from the **System Explorer** by double-clicking. Add multiple wave lengths
4. In the **Settings** of the **Layout** tab: reduce **Number Of Rays** to 1, and **Color Rays By** to **Wavelength #**
5. Show the spot diagram: **Analyze – Rays & Spots – Standard Spot Diagram**



System Explorer

Update: All Windows

5.0

Apodization Type: Uniform

Clear Semi Diameter Margin: 1.0

Clear Semi Diameter Margin: 0.0

Global Coordinate Reference: 4

Telecentric Object Space

Afocal Image Space

Iterate Solves When Upd

Fast Semi-Diameters

Check GRIN Apertures

Fields

Open Field Data Editor

Settings

Field 1 (X = 0.000, Y = 0.000)

Field 2 (X = 0.000, Y = 10.000)

Add Field

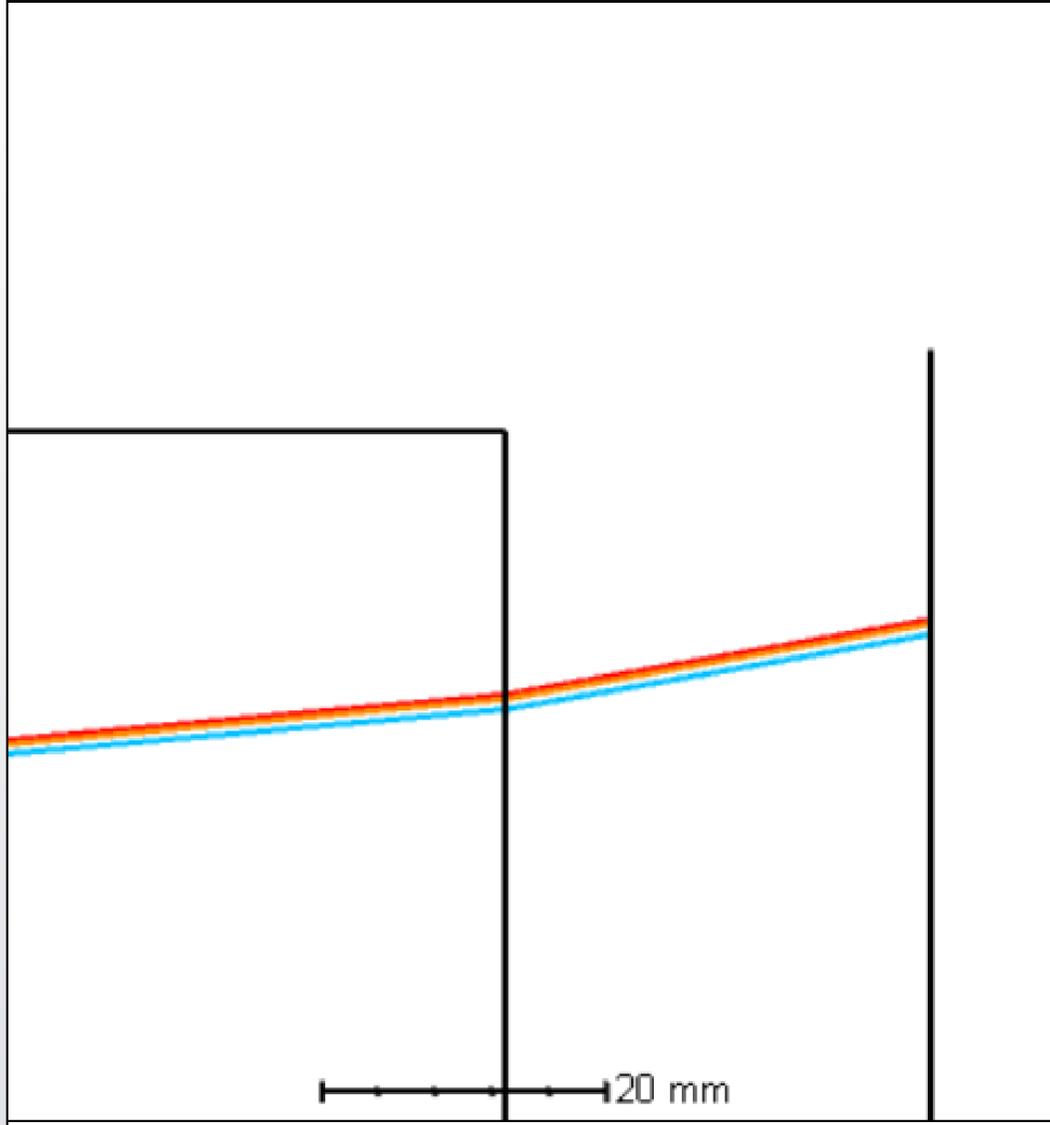
Wavelengths

Settings

Lens Data Field Data Editor 1: Layout

Settings

Line Thickness



10/17/2025  
Total Axial Length: 630.00000 mm

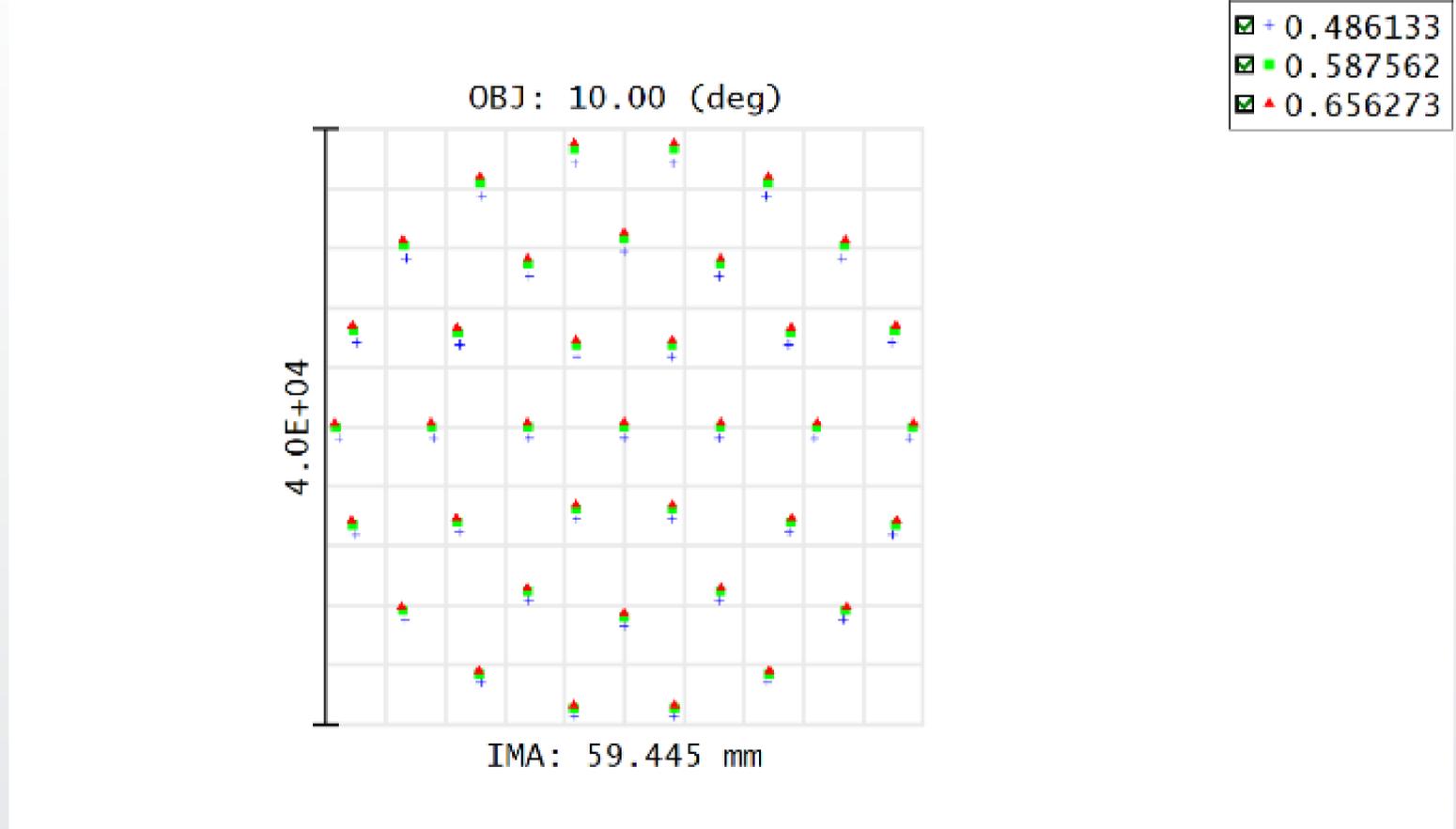
Zemax  
Ansys Zemax OpticStudio 2024 R1.00

Ex3\_wavelengths.zos  
Configuration 1 of 1

3: Spot Diagram

Settings

Automatic



Surface: IMA

Spot Diagram

10/17/2025	Zemax
Units are $\mu\text{m}$ . Legend items refer to Wavelengths	Ansys Zemax OpticStudio 2024 R1.00
Field : 2	
RMS radius : 1.5E+04	
GEO radius : 2.0E+04	
Scale bar : 4.0E+04	Reference : Chief Ray

Graph Text

