
Advanced fundamental of OSLO

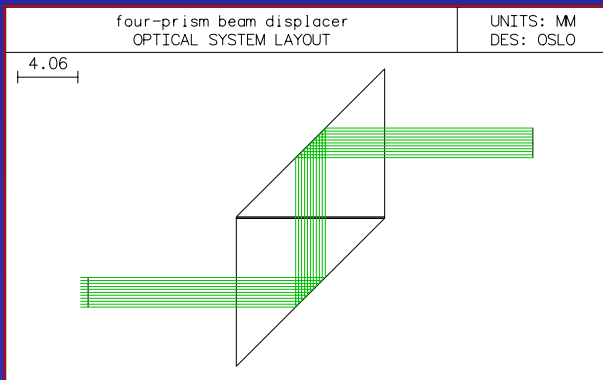
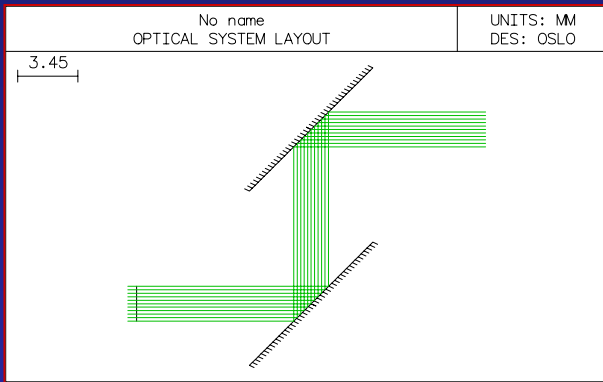
-
- Global optimization
 - Non-sequential ray tracing
 - Diffraction optics
 - Gaussian beam
 - Polarization calculation

Example 2

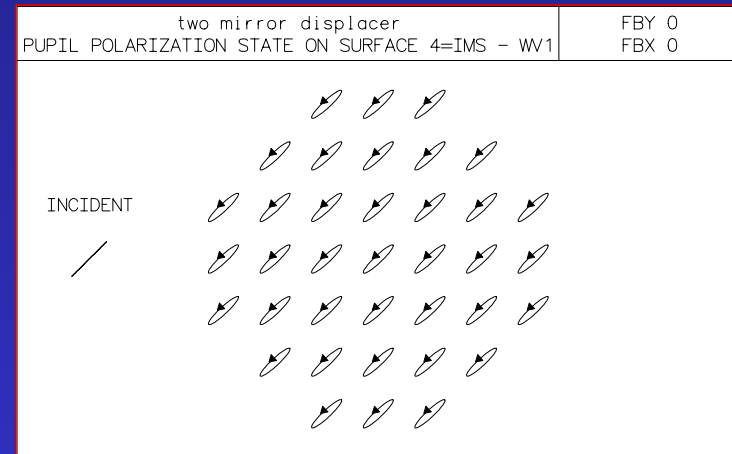
Four-prism configuration beam displacer (achromatic polarization-preserving)

Introduction to beam displacer

- Traditional beam displacer



- If it requires that linear polarization be preserved, then these two systems will work only if the state of polarization is *p*- or *s*-polarization.



Phase delay

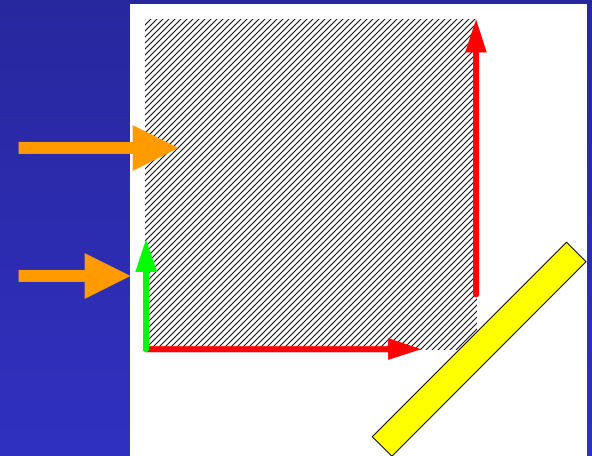
- Definition
 - p -polarization : the polarization which is parallel to the incident plane.
 - s -polarization : the polarization which is perpendicular to the incident plane.
- The relative phase shift after total internal reflection

$$\delta = \delta_p - \delta_s$$

$$\tan \frac{\delta}{2} = \frac{\cos \theta_i \sqrt{\sin^2 \theta_i - n^2}}{\sin^2 \theta_i}$$

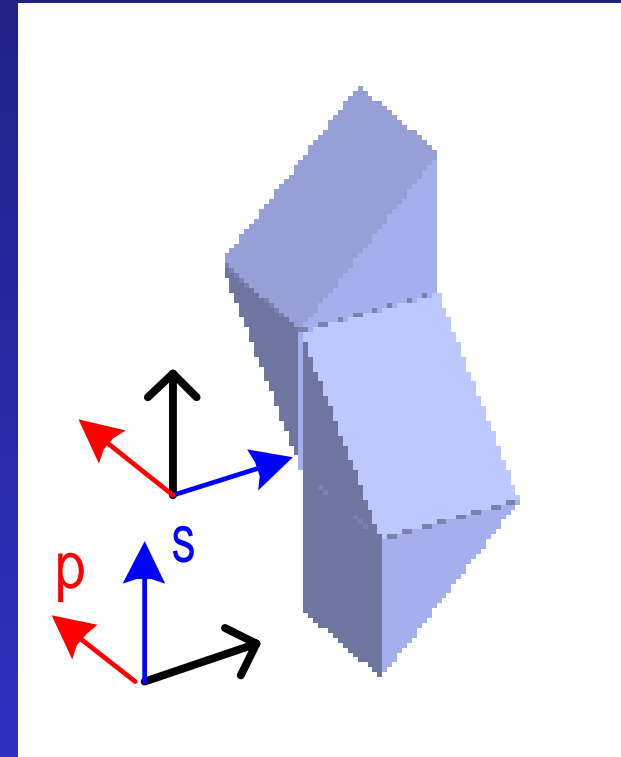
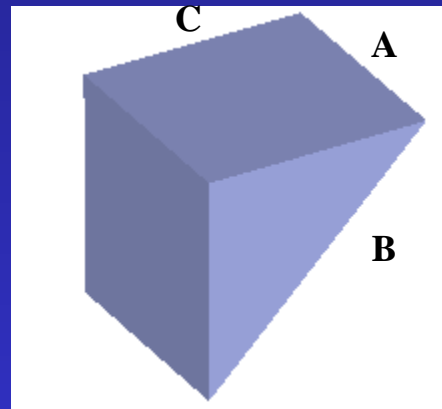
Incident plane

p -polarization



Specification

- Prism
 - Size :
 - A= 10 mm
 - B= 14 mm
 - C= 10 mm
 - Material : BK7
 - The four prisms are cemented together with refractive index-matching epoxy.

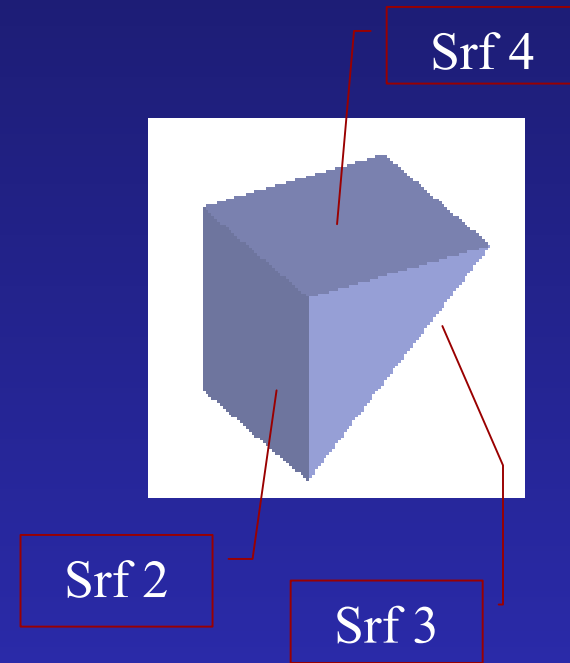


Procedure

- Step 1: building the system
 - specifying the layout of the system.
 - Defining the parameter of these prisms.
- Step 2 : polarization ray tracing

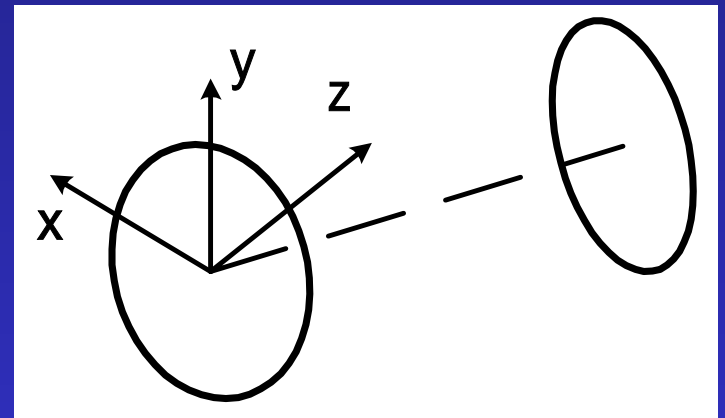
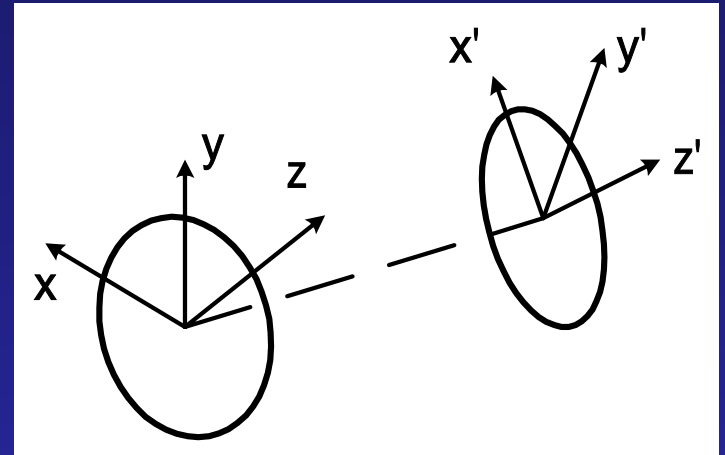
Building the prism

1. Using the “special aperture data” to define the rectangular shape aperture of each surface.
2. Srf 3 and Srf 4 should define the surface tilting and decenter.
3. We define “total internal reflection” on Srf 3.
4. We also define “anti-reflecting coatings” on Srf 2 and Srf 4.



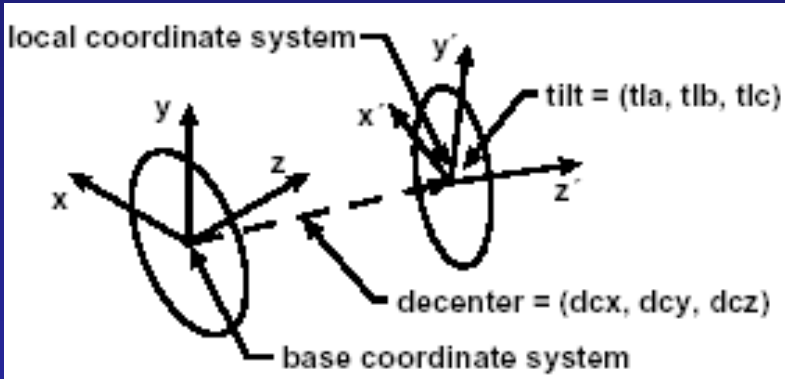
Surface coordinate

- Local coordinate
 - Each surface is described in a local coordinate system, whose origin is relative to a base coordinate system for that surface.
- Global coordinate
 - The coordinate at each surface relates to the base coordinate system of the global reference surface.

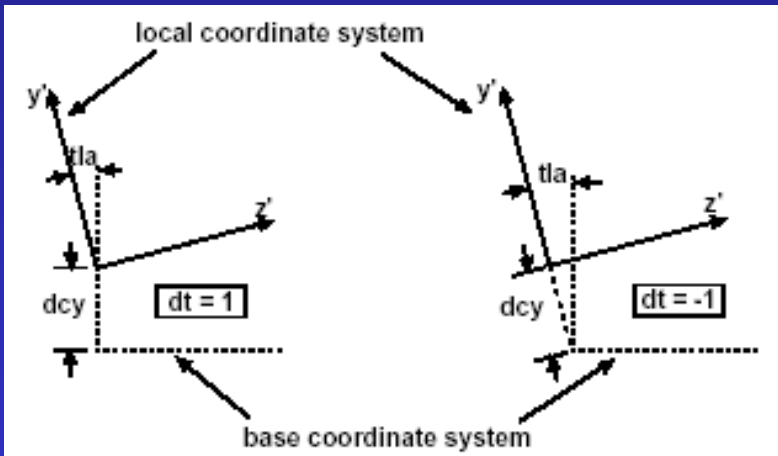
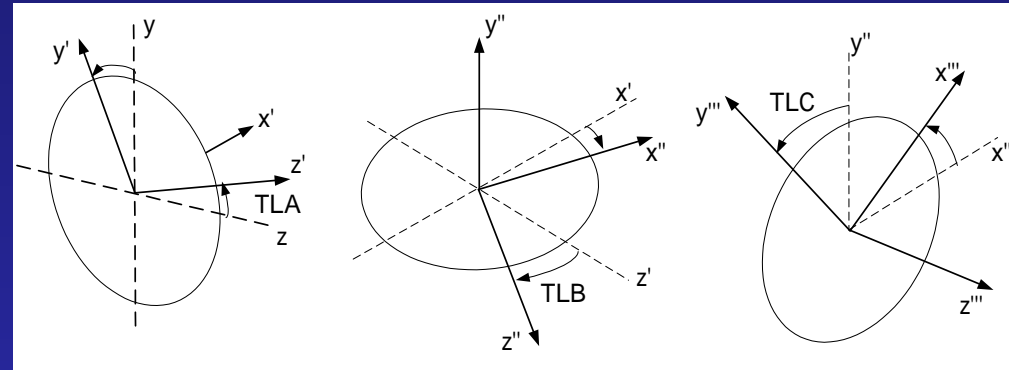


Surface coordinate

- Surface tilt and decenter



- The definition of TLA, TLB and TLC.



Defining surface coordinates

Coordinate Data < Surface Data

Surface 3 (in Element Grp)

Position - Tilt Order:

Position Referenced to surface: 2

| X | Y | Z |
|----------|----------|----------|
| 0.000000 | 0.000000 | 5.000000 |

| Rotation Angles (degrees) | | | Offset of Tilt Vertex | | |
|---------------------------|----------|----------|-----------------------|----------|----------|
| TLA | TLB | TLC | TOX | TOY | TOZ |
| -45.000000 | 0.000000 | 0.000000 | 0.000000 | 0.000000 | 0.000000 |

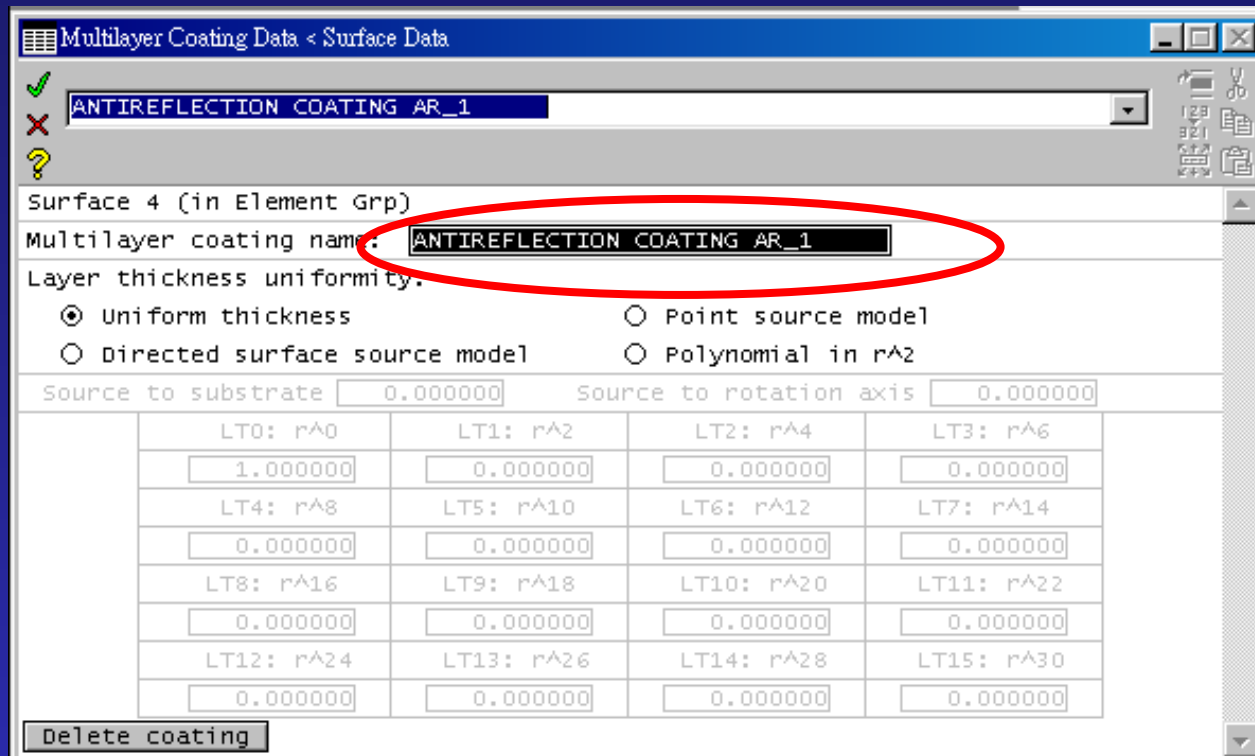
Pickup type:

Coordinates: Global reference surface:

Coordinate return:

Use base coordinate system for coordinate returns to this surface:

Setting anti-reflection coatings

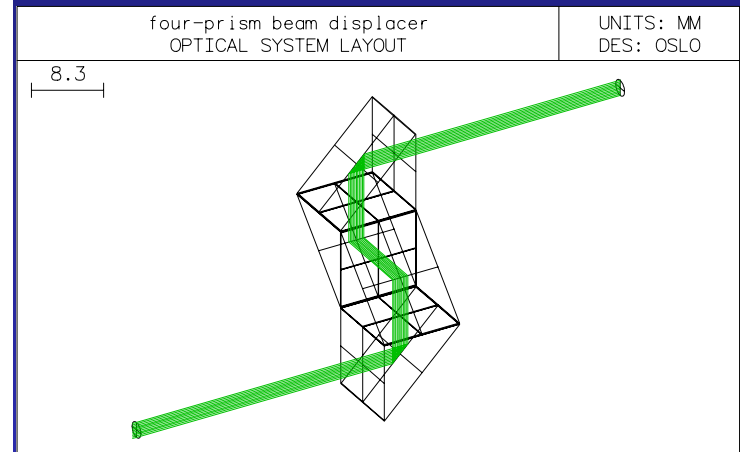


```
*MULTILAYER COATING DATA - ANTIREFLECTION COATING AR_1
REFERENCE WAVELENGTH IN AIR:    0.520000 MICROMETERS
LAYER THICKNESSES ARE MICROMETERS (OPTICAL THICKNESS)
LAYER ORDERING: SUBSTRATE TO INCIDENT MEDIUM
LAYER  THICKNESS  MATERIAL/INDEX  EXTINGT COEF
  1      0.130000          MGF2
```

Surface data and system feature

```
*LENS DATA
four-prism beam displacer
```

| SRF | RADIUS | THICKNESS | APERTURE RADIUS | GLASS | SPE | NOTE |
|-----|--------|------------|-----------------|-------|-----|------|
| OBJ | -- | 1.0000e+20 | 1.0000e+14 | AIR | | |
| AST | -- | 30.000000 | 1.000000 AS | AIR | * | |
| 2 | -- | -- | 1.000030 SX | N-BK7 | C * | |
| 3 | -- | -- | 1.000033 SX | AIR | * | |
| 4 | -- | -- | 1.000033 SX | AIR | * | |
| 5 | -- | -0.100000 | 1.000033 SX | N-BK7 | P * | |
| 6 | -- | -- | 1.000033 SX | N-BK7 | P * | |
| 7 | -- | -- | 1.000037 SX | AIR | * | |
| 8 | -- | -- | 1.000037 SX | AIR | * | |
| 9 | -- | 0.100000 | 1.000037 SX | N-BK7 | P * | |
| 10 | -- | -- | 1.000037 SX | N-BK7 | P * | |
| 11 | -- | -- | 1.000040 SX | AIR | * | |
| 12 | -- | -- | 1.000040 SX | AIR | * | |
| 13 | -- | -0.100000 | 1.000040 SX | N-BK7 | P * | |
| 14 | -- | -- | 1.000040 SX | N-BK7 | P * | |
| 15 | -- | -- | 1.000043 SX | AIR | * | |
| 16 | -- | 30.000000 | 1.000043 SX | AIR | * | |
| 17 | -- | -- | 1.000073 S | AIR | * | |
| IMS | -- | -- | 1.000073 S | | | |



Polarization calculation

- OSLO using Fresnel equations to calculate the polarization state being tracing through an optical system.

- Ellipse polarization

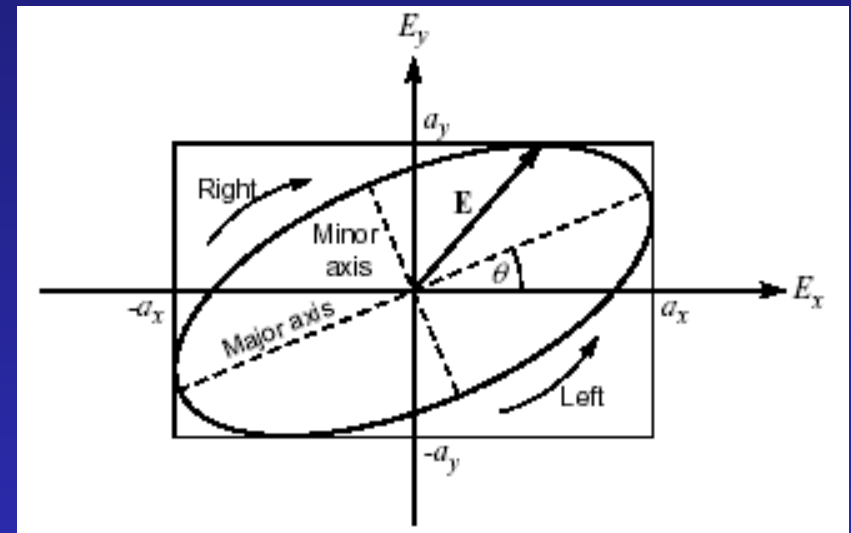
$$E_x = a_x \cos(\omega t - \vec{k} \cdot \vec{r} + \delta_x)$$

$$E_y = a_y \cos(\omega t - \vec{k} \cdot \vec{r} + \delta_y)$$

- Polarization ellipse :
e = minor axis / major axis

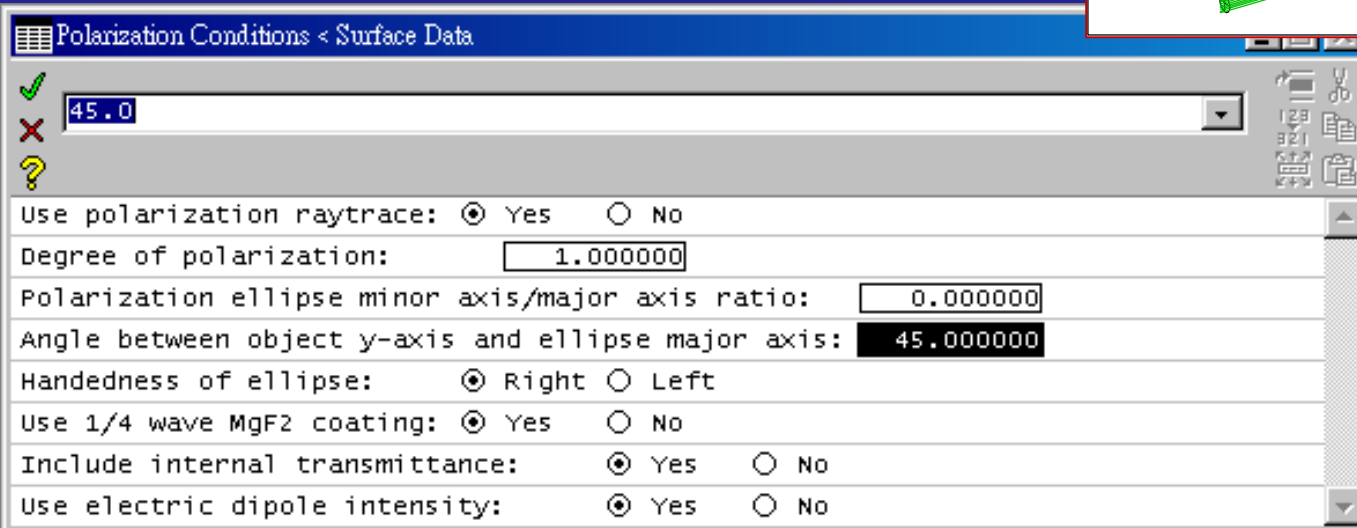
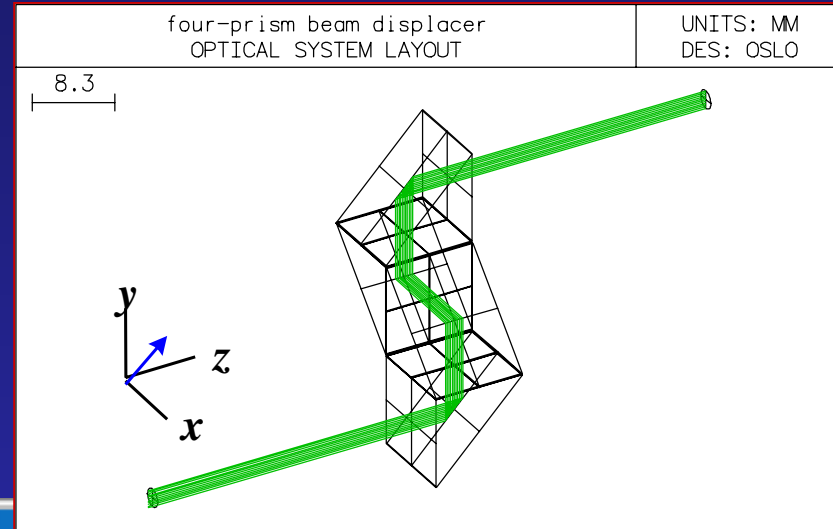
$$\tan 2\theta = \frac{2a_x a_y}{a_x^2 - a_y^2} \cos \delta$$

$$\delta = \delta_y - \delta_x$$

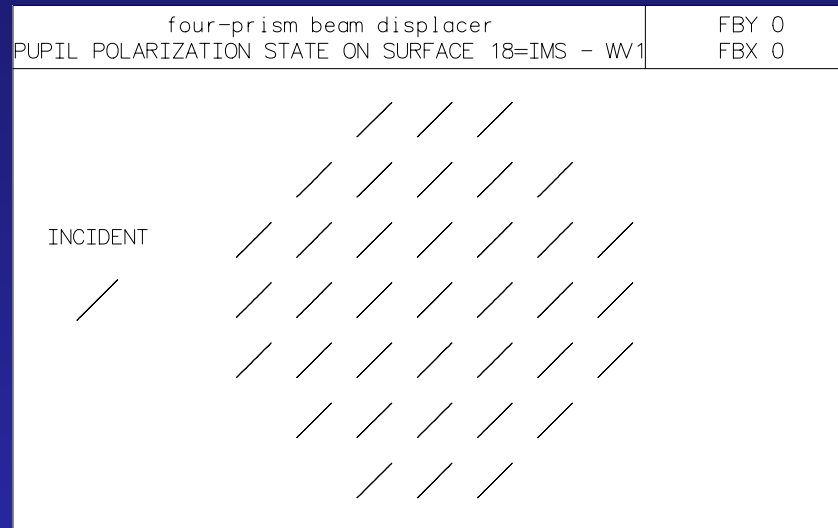


Defining the initial polarization state

- We assume the initial polarization is perfect linear which has a 45 degree angle relative to the y axis.



Evaluate final state of polarization



```
*TRACE RAY - LOCAL COORDS - FBY 0.00, FBX 0.00, FBZ 0.00
```

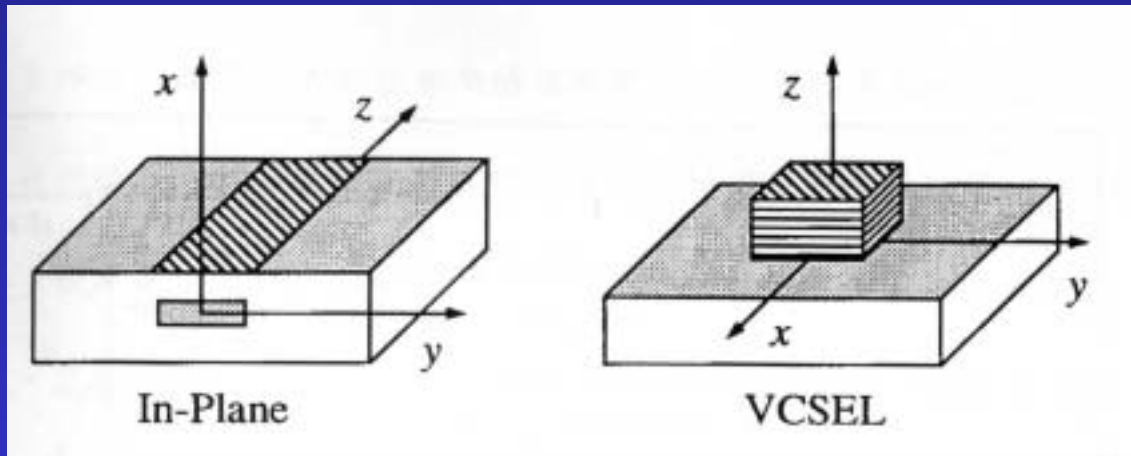
| SRF | Y/L | X/K | Z/M | YANG/IANG | XANG/RANG | D/OPL |
|-------|-------------|-------------|-----------------|-------------|-------------|------------|
| | INTENSITY | DEG. POLRZ. | ELL. RATIO | ELL. ANGLE | HANDEDNESS | |
| 18 | -1.8326e-14 | -1.4293e-14 | -- | -1.8779e-14 | -1.8779e-14 | -- |
| | -3.2775e-16 | -3.2775e-16 | 1.000000 | -- | 2.6557e-14 | 121.058095 |
| | 0.855404 | 1.000000 | 9.5684e-17 | 45.000000 | LEFT = | -1.000000 |
| PUPIL | FY | FX | RAY AIMING | | | OPD |
| | -- | -- | CENTRAL REF RAY | | | -- |

Example 3

Effective lens model of VCSEL

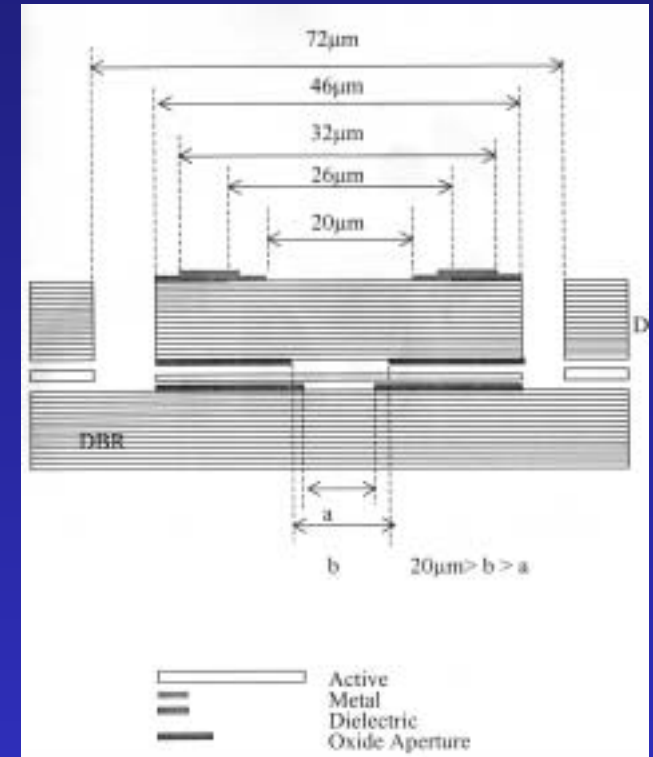
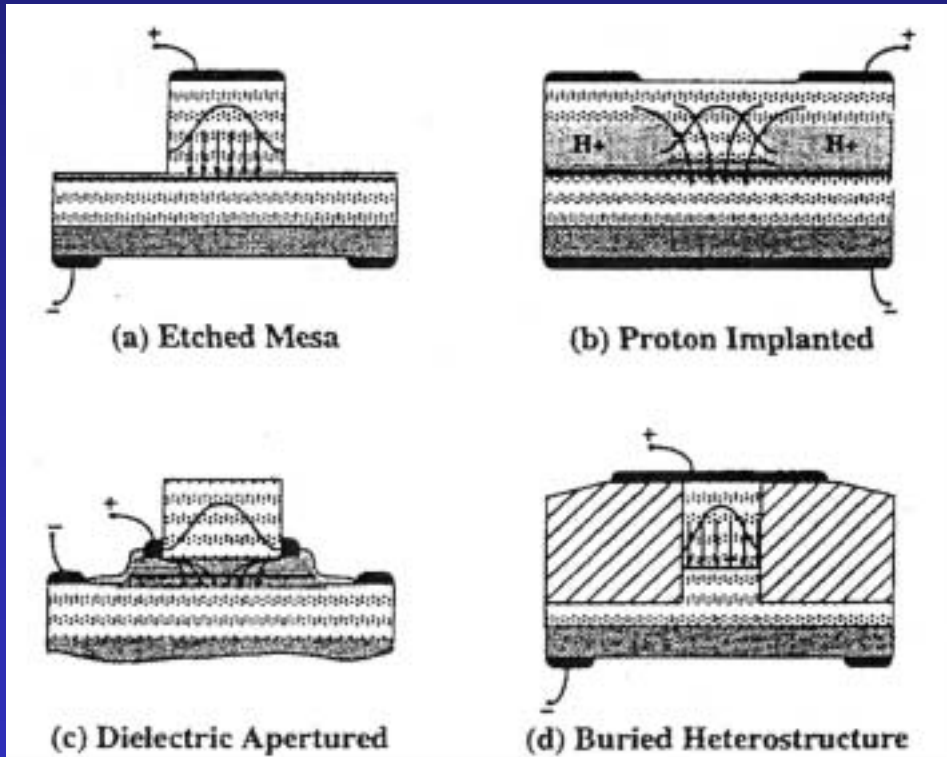
Introduction of VCSEL

- VCSE: Vertical Cavity Surface Emitting Lasers
- VCSEL is a kind of semiconductor lasers. But unlike common semiconductor lasers, it emits laser light vertically.
- Since the cavity is cylindrical shape, the emission mode of VCSEL is also in symmetrical shape. Nevertheless, VCSEL also can emit donut-like field pattern (whispering gallery mode)



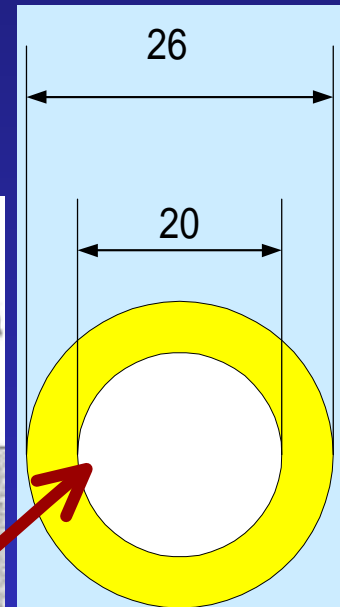
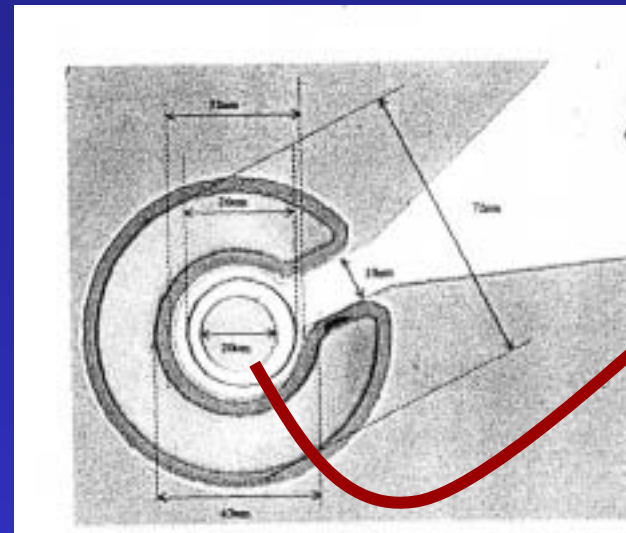
Introduction of VCSEL

- The construction of VCSEL



Specification

- We would like to build an effective lens model to simulate a VCSEL with donut-like field pattern.
- Furthermore, we would like to evaluate the coupling efficiency with fiber. Let us have the specification first.
 - Wavelength : 850 nm
 - Laser diode :
 - Emitting area
 - Outside circle diameter : 26 μm
 - Inside circle diameter : 20 μm
 - Half-Divergence angle : 8 degree
 - Fiber:
 - Core ~ 5 μm
 - N.A. ~ 0.3



Classification and Question

- Typical LD (semiconductor lasers)
 - Astigmatic sources to simulate elliptic Gaussian mode
 - Two point sources separated by an astigmatism distances.
- Typical VCSEL
 - Using point source with Gaussian ray tracing to simulate the perfect Gaussian mode
- Question
 - How to simulate Donut-pattern VCSEL?

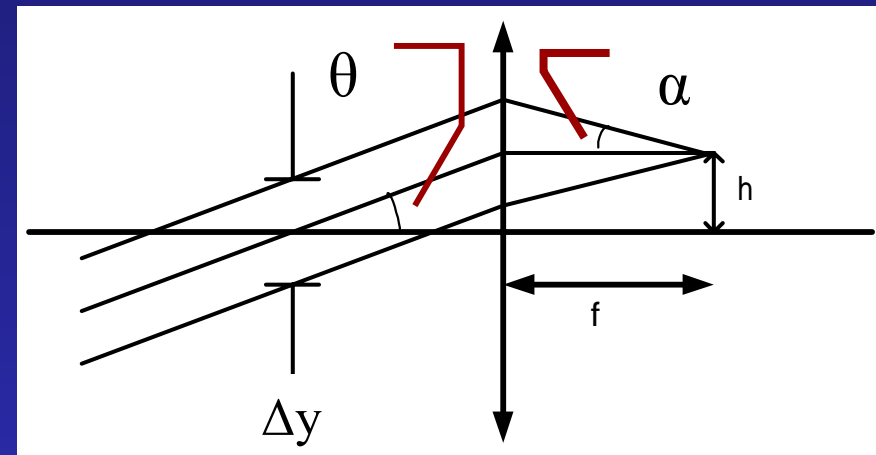
Algorithm

- The modified model


$$f = h \tan \theta$$

$$\tan \alpha = \frac{\Delta y}{2f}$$

- α :divergence angle
- h : radius of emitting area
- f : focal length of perfect length
- θ : field angle of the defined object
- Δy :diameter of defined aperture



Calculation

- 
- Divergence angle $\alpha=8$ degree
 - Emitting area radius
 - outside circle : $h=0.013$ mm
 - inside circle : $h'=0.01$ mm
 - Focal length of perfect lens: 1mm

$$f = h \tan \theta$$



$$\theta=0.744803178 \text{ degree}$$

$$\tan \alpha = \frac{\Delta y}{2f}$$



$$\Delta y=0.140540834 \text{ mm}$$

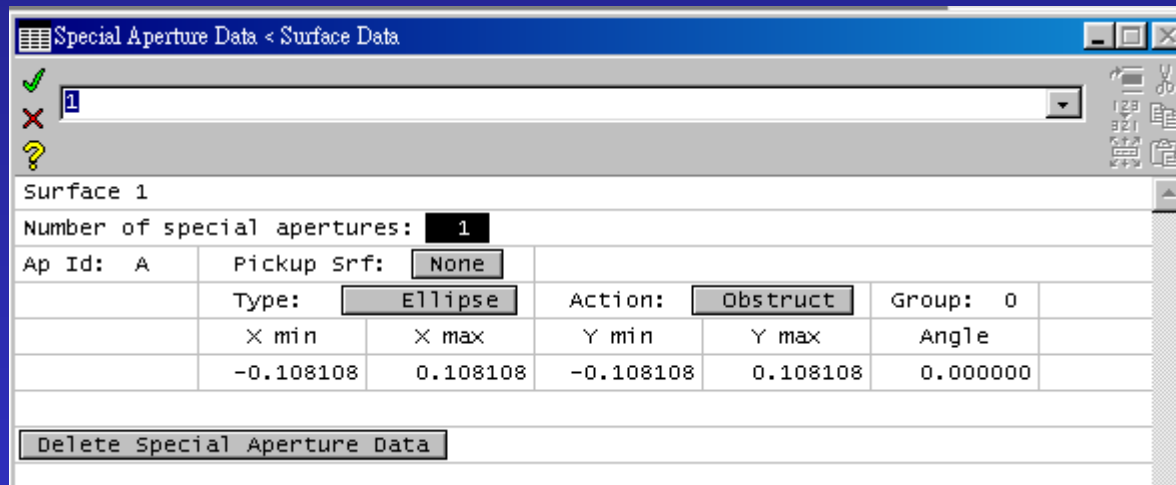
$$\frac{h}{h'} = \frac{\Delta y}{\Delta y'}$$



$$\Delta y'=0.108108333 \text{ mm}$$

Building effective lens model of VCSEL

- Step 1: Defining the aperture
 - Set the ring aperture on Srf 1, enter Δy as the aperture radius and define it as the aperture stop.
 - Click the “Special Aperture Data” menu on Srf 1, select “Obstruct” and enter $\Delta y'$ as the boundary.



Building effective lens model of VCSEL

- Step 2: Build the perfect lens
 - Click “Perfect lens” on the “Special” button, enter focal length.

The screenshot displays the Zemax software interface. On the left, the 'Perfect Lens Data < Surface Data' dialog box is open, showing 'Surface 2' with a focal length of 1.000000 and magnification of 0.000000. On the right, a ray diagram shows a beam converging to a focal point at a distance of 0.341. Below the ray diagram, the 'Lens Data Editor' is visible, showing the lens configuration for a VCSEL.

VCSEL
FOCAL LENGTH = 1 NA = 0.1405
UNITS: MM
DES: OSLO

0.341

Perfect Lens Data < Surface Data

1.0

Surface 2

Focal length: 1.000000

Magnification: 0.000000

Delete Perfect Lens

Gen Setup Wavelength Field Points Variables Draw On Group Notes

Lens: VCSEL Zoom 1 of 1 Efl 1.000000

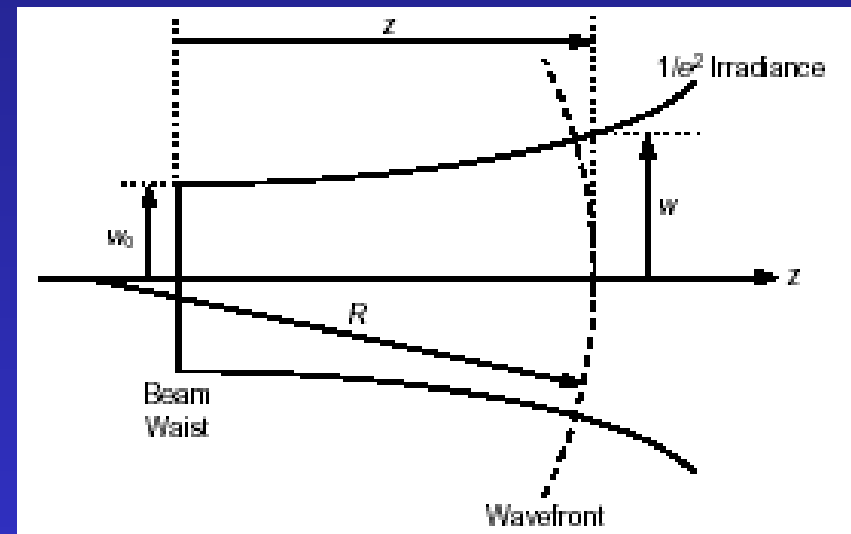
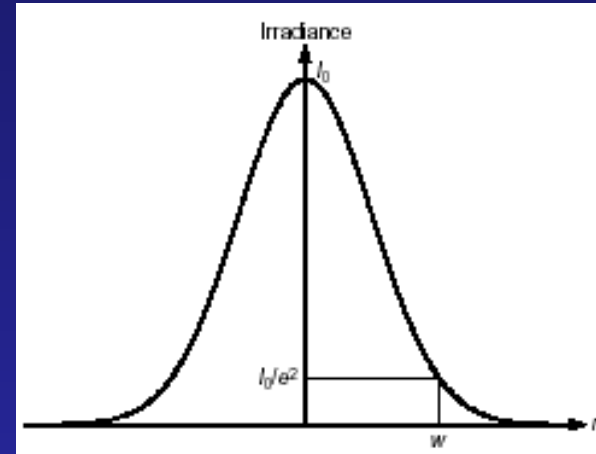
Ent beam radius 0.140541 Field angle 0.744803 Primary wavln 0.850000

| SRF | RADIUS | THICKNESS | APERTURE RADIUS | GLASS | SPECIAL |
|-----|----------|------------|-----------------|-------|---------|
| OBJ | 0.000000 | 1.0000e+20 | 1.3000e+18 | AIR | |
| AST | 0.000000 | 1.000000 | 0.140541 | AX | F |
| 2 | 0.000000 | 1.000000 | 0.153541 | S | L |
| 3 | 0.000000 | 1.000000 | 0.013000 | S | |
| IMS | 0.000000 | 0.000000 | 0.153541 | S | F |

Gaussian beam ray trace

- The algorithm is ABCD matrix.
- The formula of $\omega(z)$ and $R(z)$.

$$\omega^2(z) = \omega_0^2 \left[1 + \left(\frac{\lambda}{\pi \omega_0^2} \right)^2 z^2 \right]$$
$$R(z) = z \left[1 + \left(\frac{\pi \omega_0^2}{\lambda z} \right)^2 \right]$$



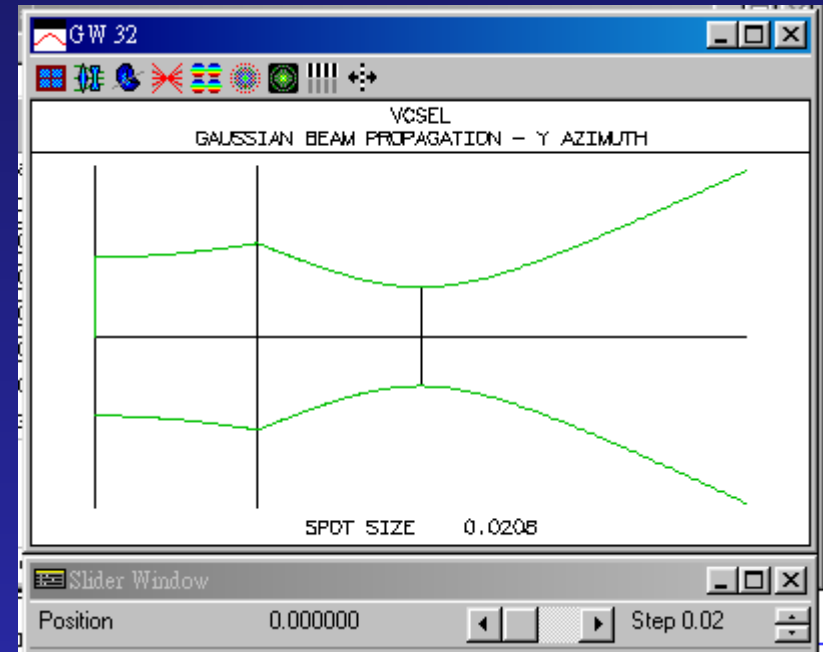
Gaussian beam ray trace

- Step 1 : observing Gaussian beam propagation
 1. Use “Source >> Paraxial Gaussian Beam(ABCD)”.
 2. We should specify a surface to be a reference surface in calculation.
 3. Enter parameters which could define a gaussian beam.

| Beam Specification Surface: <input type="text" value="3"/> | | | Beam Evaluation Surface: <input type="text" value="4"/> | | |
|--|---------------------------------------|---------------------------------------|--|---------------------------------------|---------------------------|
| | Solution I | Solution II | | Solution I | Solution II |
| Spot size (w) | <input type="text" value="0.013000"/> | 0.000000 | Spot size (w) | 0.043608 | 0.000000 |
| Waist ss (w0) * | <input type="text" value="0.013000"/> | 0.000000 | Waist ss (w0) | 0.013000 | 0.000000 |
| Waist dist (z)* | <input type="text" value="0.000000"/> | 0.000000 | Waist dist (z) | -2.000000 | 0.000000 |
| Wvf radius (R) | <input type="text" value="0.000000"/> | 0.000000 | Wvf radius (R) | -2.195077 | 0.000000 |
| Diverg. (rad) | 0.020810 | 0.000000 | Diverg. (rad) | 0.020810 | 0.000000 |
| Rayleigh range | 0.624623 | 0.000000 | Rayleigh range | 0.624623 | 0.000000 |
| Wavelength number of beam | | <input type="text" value="1"/> | Evaluation surface shift | <input type="text" value="0.000000"/> | |
| Wavelength | | 0.850000 | Beam meridian: | <input checked="" type="radio"/> y-z | <input type="radio"/> x-z |
| M-squared | | <input type="text" value="1.000000"/> | <input type="button" value="Print beam data in text window"/> | | |
| <input type="button" value="Plot beam spot size"/> | | | <input checked="" type="radio"/> slider-wheel design <input type="radio"/> Current graphics window | | |

Observing Gaussian beam propagation

- We could choose the “Plot beam spot size” to observe the graphical Gaussian beam propagation or “Print beam data in text window” to check the Gaussian beam on each surface.

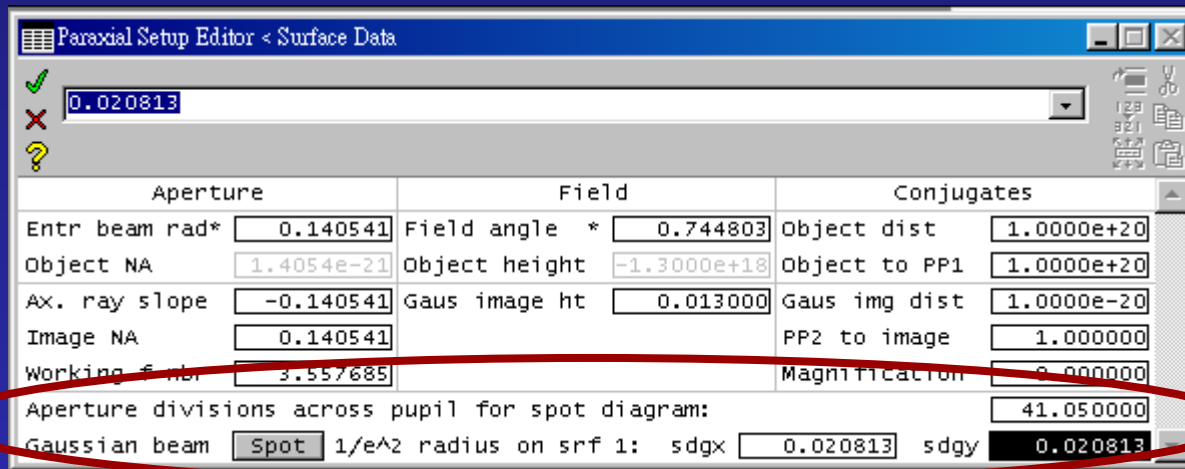


```
*GAUSSIAN BEAM - YZ PLANE
WAVELENGTH = 0.850000    M-SQUARED = 1.000000
SRF SPOT SIZE DIVERGENCE WAIST SIZE WAIST DIST INC RADIUS RFR RADIUS RAYLEIGH RG
INC 0.020813 0.012999 0.020813 -- -- -- 1.600967
1 0.020813 0.012999 0.020813 -- -- -- 1.600967
2 0.024539 0.020810 0.013000 1.000000 -3.563095 1.390153 0.624623
3 0.013000 0.020810 0.013000 -- -- -- 0.624623
4 0.043608 0.020810 0.013000 -2.000000 -2.195077 -2.195077 0.624623
```

The table displays the Gaussian beam parameters at four different surfaces (SRF 1 to 4). The columns are: SRF, SPOT SIZE, DIVERGENCE, WAIST SIZE, WAIST DIST, INC RADIUS, RFR RADIUS, and RAYLEIGH RG. The SPOT SIZE and WAIST SIZE columns are circled in red in the original image.

Guassian beam ray trace

- Step 2: setting Guassian beam
 - We set the “ $1/e^2$ radius on Srf 1” equal to Guassian beam spot size on Srf 1 obtained by step 1.



Guassian beam ray trace

- Step 3: Guassian beam ray trace

Trace Gaussian beam

Output format control

Standard (Print beam size and wavefront radius of curvature)

Full (Add waist size and location to output)

Surface selection option

Range of surfaces (Print data for specified surface range)

All surfaces (Print data at all surfaces)

Beam sizes ($1/e^2$ radius) at object surface

Y X

Wavefront radii of curvature at object surface

Y X

Azimuthal (from X-axis) orientation angle of beam

First surface number Last surface number

M-squared value (1.0 for Gaussian beam)

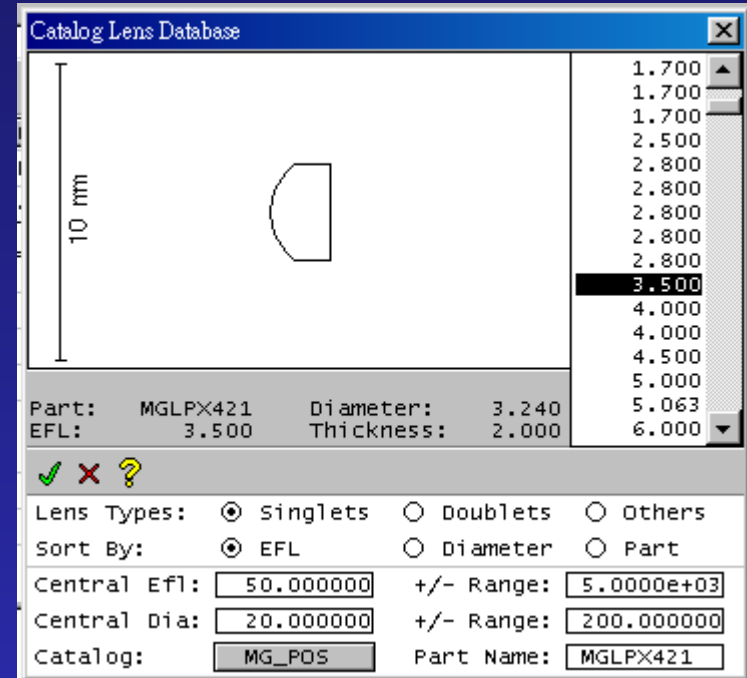
Set Object Point

OK Cancel Help

```
*TRACE GAUSSIAN BEAM
WAVELENGTH = 0.850000 M-SQUARED = 1.000000
SRF Y SPT SIZE X SPT SIZE BEAM AZMTH Y RFR RAD X RFR RAD PHASE AZMTH
Y WST SIZE X WST SIZE Y WST DST X WST DST
INC 0.020813 0.020813 -- -- -- --
0.020813 0.020813
1 0.020813 0.020813 -- -1.8327e+13 -1.8327e+13 --
0.020813 0.020813 -1.3987e-13 -1.3987e-13
2 0.024539 0.024539 -- 1.390121 1.390121 --
0.013000 0.013000 1.000000 1.000000
3 0.013000 0.013000 -- -5.6026e+09 -5.6026e+09 --
0.013000 0.013000 -6.9632e-11 -6.9632e-11
4 0.024539 0.024539 -- -1.390121 -1.390121 --
0.013000 0.013000 -1.000000 -1.000000
```

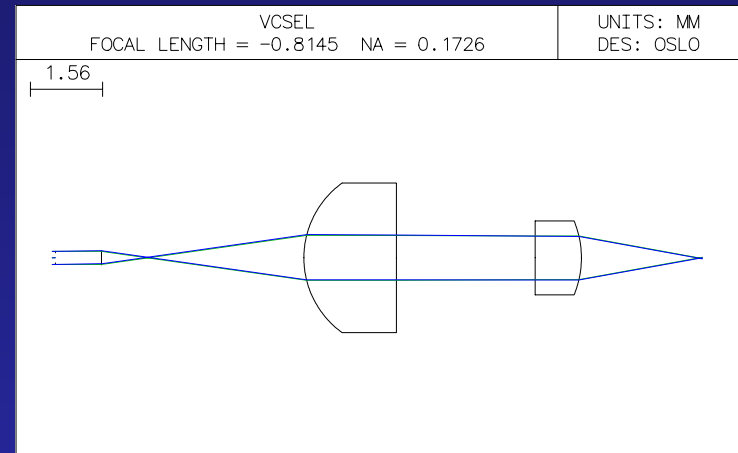
Build a collimating lens

- We could use the “catalog lens” to build a focusing lens.
- Right-clicking on Srf 4 and select insert “catalog lens”.
- Select the part number “MGLPX421” on the “MG_POS” catalog.



Set focus lens

- Since the numerical aperture of fibers is 0.3, we can choose any focusing lens with numerical aperture smaller than 0.3.
- We design a focusing lens with diameter 1.6mm, numerical aperture 0.29 and SF4 material.



VCSEL



Collimating lens



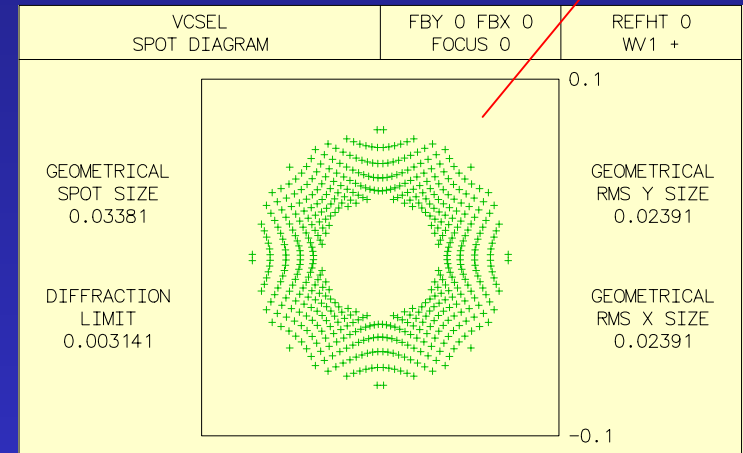
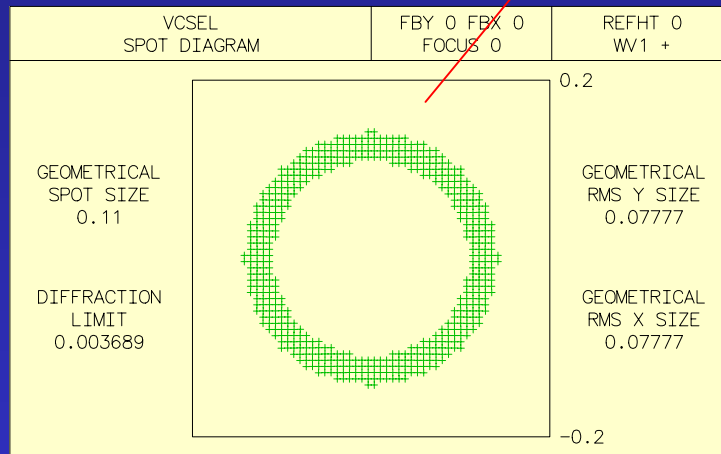
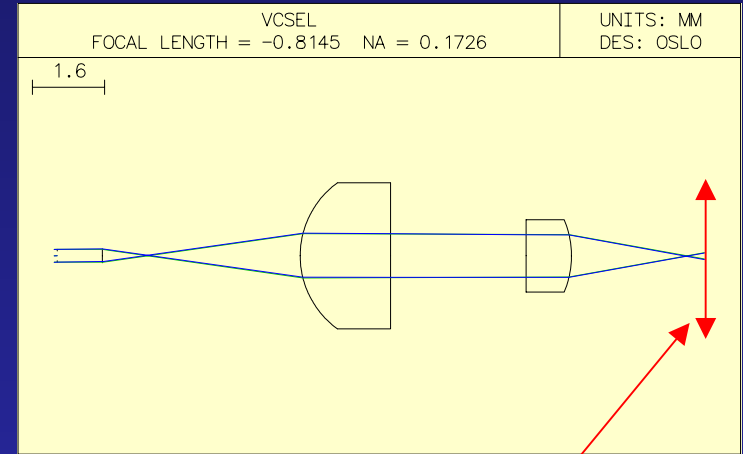
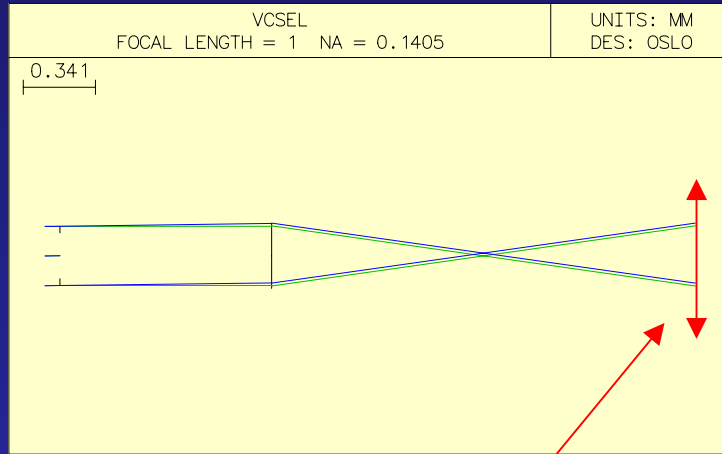
focusing lens



```

*LENS DATA
VCSEL
SRF      RADIUS      THICKNESS  APERTURE RADIUS  GLASS  SPE  NOTE
OBJ      --          1.0000e+20  1.3000e+18      AIR
AST      --          1.000000   0.140541 AX     AIR   *
2        --          1.000000 S   0.153541 S     AIR   *
3        --          3.376244   0.013000 S     AIR
4        MGLPX421 F   2.000000 F   1.620000 F     FIXED F *
5        F          3.000000   1.620000 F     AIR
6        --          1.000000   0.800000      SF4 C
7        -2.080000  2.620000   0.800000      AIR
IMS      --          --          0.066043 S     *
    
```


Simulation Result



Fiber coupling efficiency calculation

- Computation of coupling efficiency is one of the applications of point spread function.
- Coupling efficiency :

$$\eta = \frac{\iint U(x', y') \Psi^*(x', y') dx' dy'}{\sqrt{\iint U(x', y') U^*(x', y') dx' dy' \iint \Psi(x', y') \Psi^*(x', y') dx' dy'}}$$

- $U(x,y)$: amplitude diffraction function
- $\Psi(x,y)$: fiber mode pattern

Fiber coupling efficiency calculation

Compute fiber coupling efficiency

Wavelength number: 1

Fiber mode type:
 Gaussian mode Fundamental step-index mode User-defined mode

Gaussian mode $1/e^2$ radius: 0.000000

Core index: 1.500000 Cladding index: 1.469700 Core radius: 0.005000

usermode CCL command name to compute mode

Size of FFT grid:
 16 32 64 128 256 512 1024

Rays across pupil diameter (less than FFT grid size): 32

Fiber displacement in y-direction: 0.000000

Fiber displacement in x-direction: 0.000000

Fiber tilt around y-axis (TLB): 0.000000

Fiber tilt around x-axis (TLA): 0.000000

Set Object Point

OK Cancel Help

```
*FIBER COUPLING EFFICIENCY - WAVELENGTH 1
FUNDAMENTAL MODE OF STEP-INDEX FIBER
CORE INDEX =      1.500000 CLADDING INDEX =      1.469700 CORE RADIUS =      0.005000
FIBER DISPLACEMENT  Y      --      X      --
FIBER TILT           TLB      --      TLA      --
POWER COUPLING =      0.000361      ( -34.42      dB)
AMPLITUDE COUPLING  REAL = -0.0189      IMAGINARY =      0.002009
```

References

- “OLSO optical reference”
- “Modern optical engineering”, Warren J. Smith
- “Lens design”, Milton Laikin
- “Achromatic polarization-preserving beam displacer,” E. J. Galvez, Opt. Lett. Vol. 26, pp. 971-973 (2001) for example 2.
- “Astigmatic light source in optical design software,” S. Thibault, Opt. Eng. Vol.39, pp. 1808-1811 (2000) for example 3.