Feasibility analysis of different optical connectivity technologies

A contribution to OMEGA SG meeting

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Objective

1. To perform a feasibility analysis of butt-coupling (BC) and expanded beam optical (EBO) coupling technologies for automotive multi-gigabit operation.

Agenda

1. **Introduction to ray tracing based simulations:**
   - ✓ Basic concepts and general setup.
2. **Introduction and sensitivity analysis of BC Connectors.**
3. **Introduction to EBO connectors:**
   - ✓ Concept, Pros, Cons and Examples.
4. **Sensitivity analysis of EBO connectors:**
   - ✓ Main sources of tolerances, structure with plano-convex lenses, structure with ball lenses.
5. **Discussion of results.**
6. **Conclusions.**

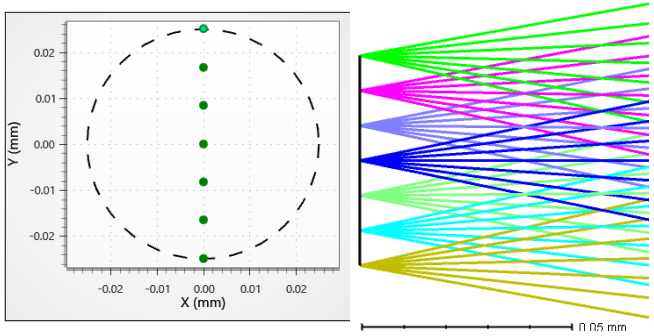
1 Introduction to ray tracing based simulations:

1. Introduction to ray tracing based simulations

In order to use geometrical rays to model multi-mode fiber coupling, the **fiber core diameter has to be at least 10 times larger than the wavelength**, such that many transverse modes can be supported.

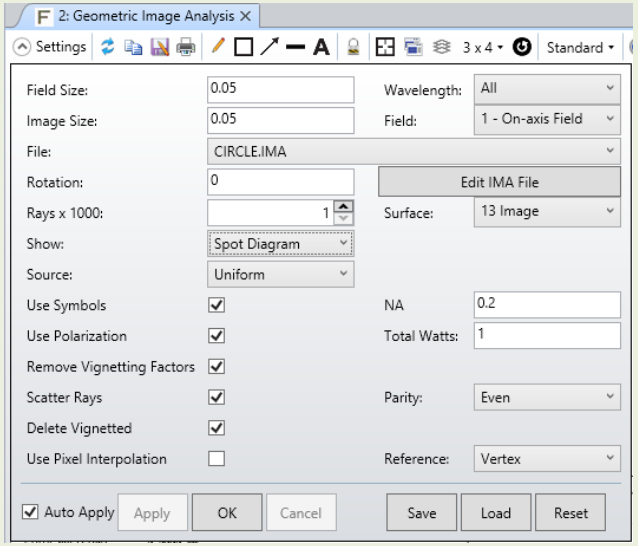
General Setup		
Wavelength	850nm	
Fiber NA	0.2	
Fiber Core	Diameter	50um
	Material	Silica
	Index Profile	Step-Index
Lenses	Material	BK7 (n = 1.51)
	Coating	AR
Coupling efficiency calculations include Fresnel Losses of the output fiber.		

Emission Fields: MMF 50um core

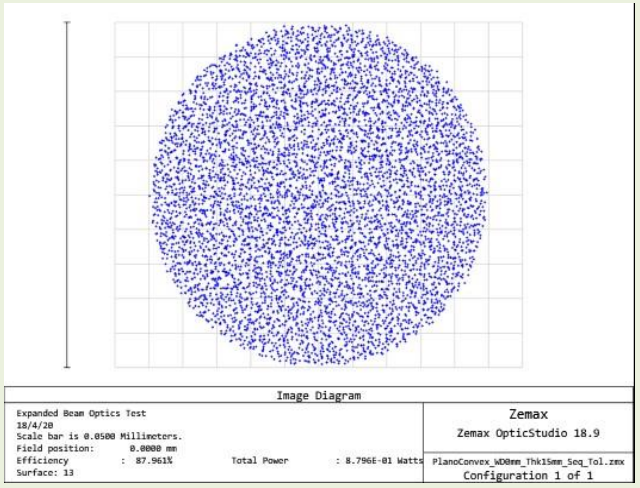


❑ Geometric Image Analysis

➢ **Setup:**



➢ **Results:**



2 Introduction and sensitivity analysis of BC connectors:

2. Introduction and sensitivity analysis of BC connectors

- Butt Coupling (BC) connections are characterized by the physical mating of two optical fibers.
- Physical Contact (PC) connector are a special type of BC where the air gap space between fibers is zero (or almost zero due to tolerances).
- Advances in ceramic manufacturing enabled high precision, physical contact fiber optic connectors with low insertion losses (ILs).
- ILs for PC connectors:
  - Typical: 0.3dB
  - Maximum: 1dB (Worst Case)
- Return Loss (RL) for PC connectors:
  - Typical: <= -30dB
  - Maximum: -26dB (for worst case IL)

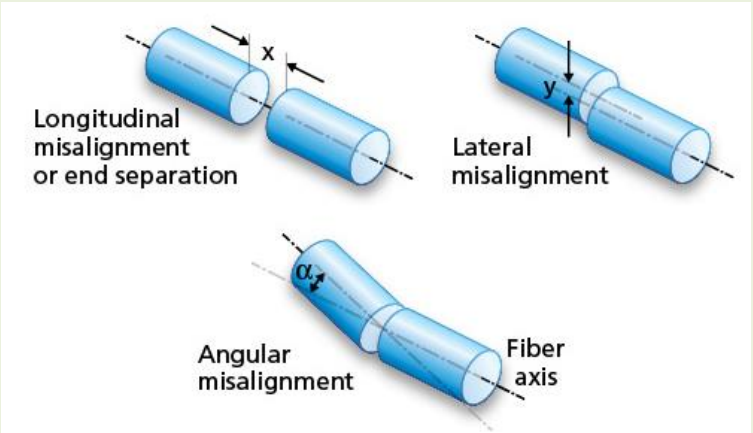
Flat
RL < -30dB

PC
RL < -35dB

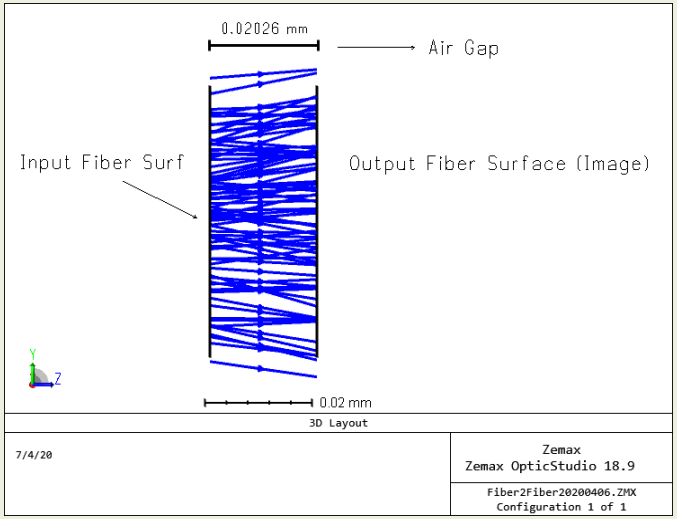
Ultra PC
RL < -55dB

Angled PC
RL < -65dB

Misalignment Losses



Ray Tracing Setup



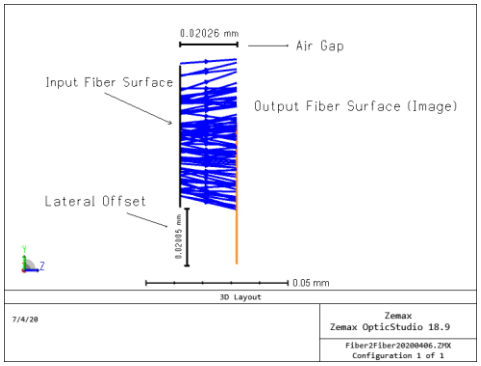
Fiber-to-fiber butt coupling simulation scheme.

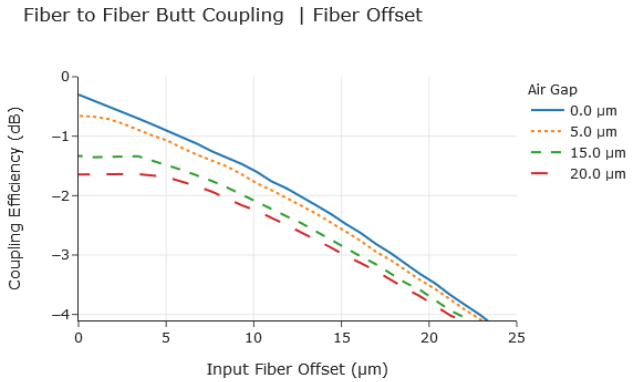
2. Introduction and sensitivity analysis of BC connectors

Lateral Misalignment

- **High sensitivity to air gap:** Coupling efficiency drops 1dB with an air gap of 15um.
- **High sensitivity to fiber offset:** Coupling efficiency drops 1dB with an offset of 7um.
- The positioning tolerance (offset and airgap) must be below ±5um to keept efficiency variations bellow 1dB.

BC based connectors are quite sensitive to fiber misalignments (Offset and Air Gap).

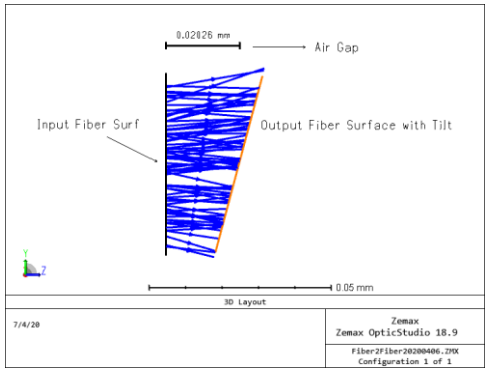


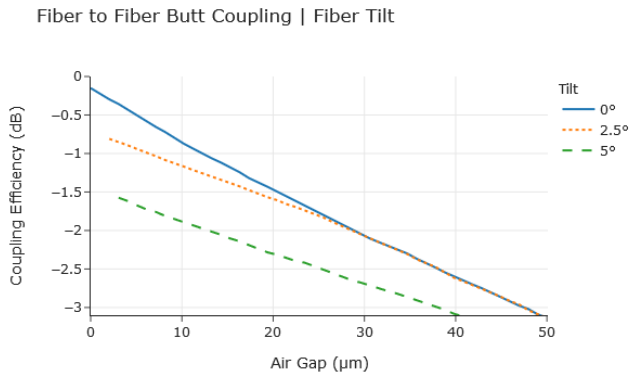


Angular Misalignment

- **Low sensitivity to tilt between fibers en-faces:**
  - Coupling efficiency variation of about **0.6dB for 2.5º tilt.**
  - Coupling efficiency variation of about 1.25dB for 5º tilt.

But coupling based connectors have low sensitivity to fiber tilt.



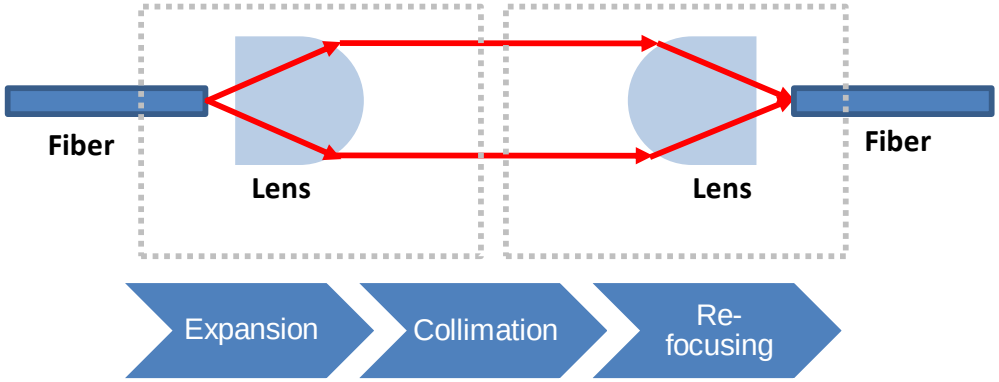


3 Introduction to EBO connectors:

3. Introduction to EBO Connectors: Concept, Pros and Cons

Expanded Beam Optics

- Expanded beam connectors use lenses in front the fibers in order to coupling the light by: expanding, collimating and re-focusing the beam.
- Beam expansion gives multiple advantages:



Pros

- High resistance to:
  - Environmental contamination.
  - Temperature variations.
  - Vibrations.
  - Shocks.
  - Optical Missalignement.
- Easy maintenance and cleaning.
- Durability

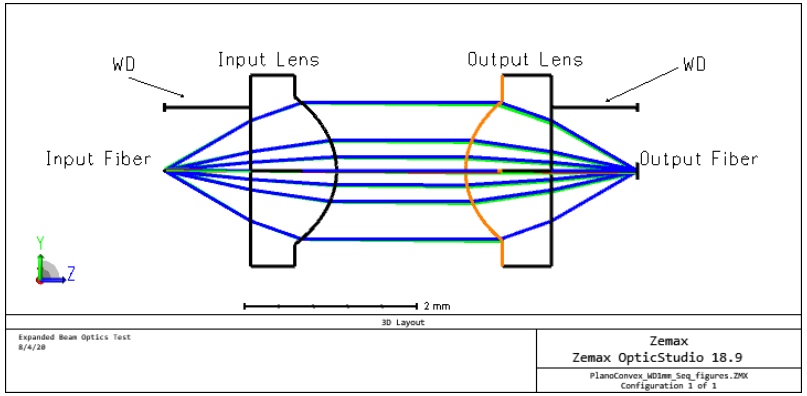
Cons

- Number of elements:
  - Increase size
  - May increase cost.
- Insertion losses:
  - EBO: ILs of about 1.5dB
  - PC: Ls of about 0.3dB.
- Return Loss:
  - EBO: RLs of about –30dB.
  - PC: RLs of about –30dB.
  - APC: RLs of about –65dB.

4 Sensitivity analysis of EBO connectors:

4. Sensitivity Analysis of EBO Connectors

General Scheme

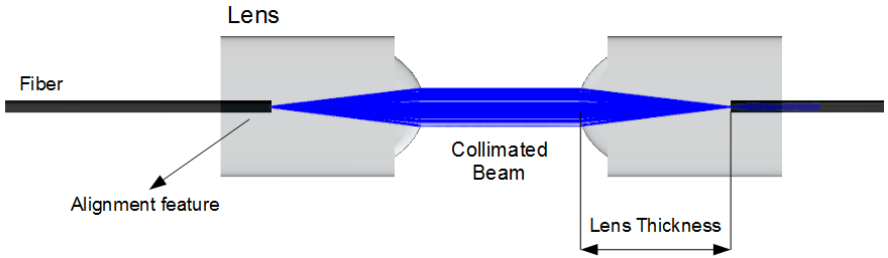


EBO connector consists of two identical lenses that are designed to generate a collimated beam between them.

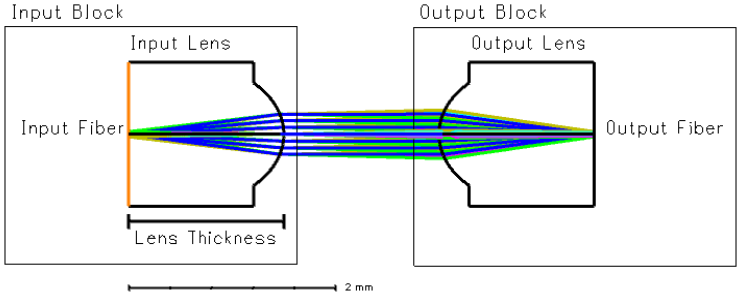
Tolerance Source	Performance Impact
Fiber Tilt	Low
Fiber Offset	High
Lens Tilt	High
Lens Offset	Very Low

It is possible to reduce the degrees of freedom. If the lens include an alignment feature and the fiber is in contact with the lens surface, the fiber tilt and offset effects can be highly reduced.

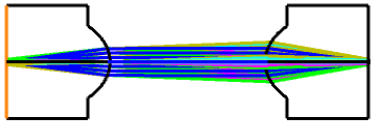
Plano-Convex lenses with alignment features



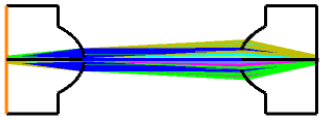
a) Thickness = 1.5mm
- Radius = 0.508
- Conic = -0.442



b) Thickness = 1.0mm
- Radius = 0.338
- Conic = -0.529



c) Thickness = 0.75mm
- Radius = 0.253
- Conic = -0.647

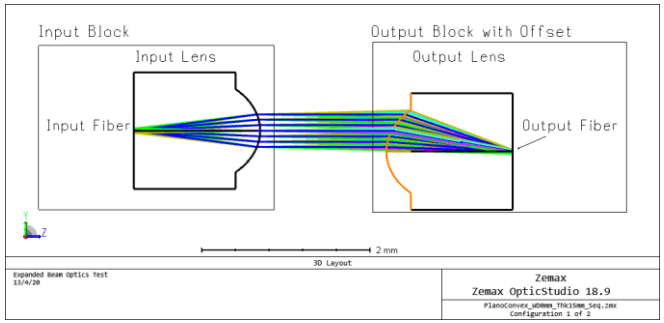


Less Collimated

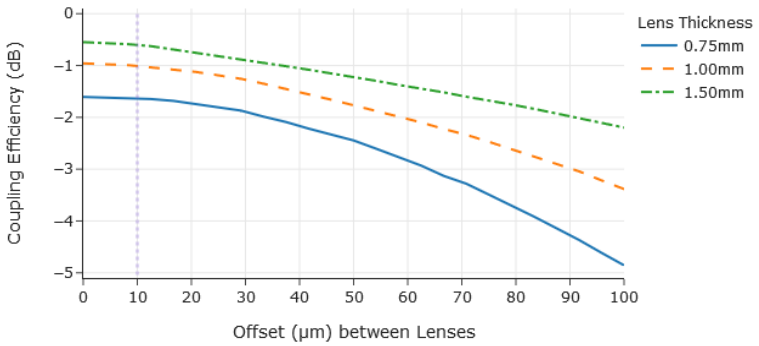
4. Sensitivity Analysis of EBO Connectors

Misalignment

Very low sensitivity



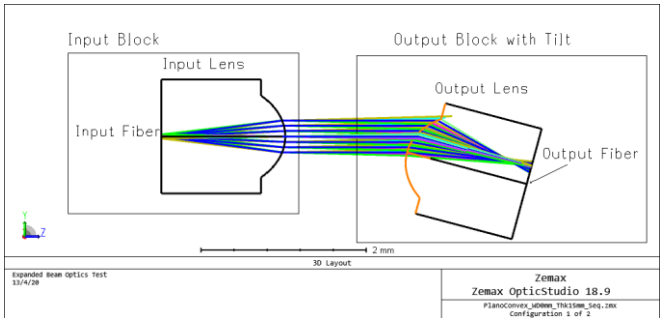
EBO Coupling - Plano-Convex Lenses | Lens Offset



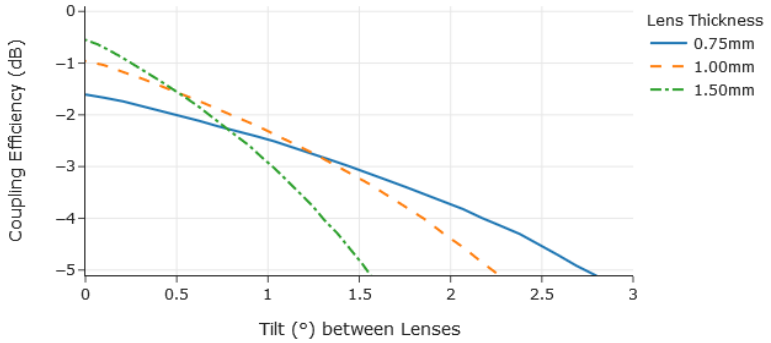
- Maximum coupling efficiency is -1.6, -0.96 and -0.55dB for thicknesses of 0.75, 1.00 and 1.50mm, respectively. The smaller the focal length, the greater the divergence and the lower the coupling efficiency.
- Efficiency variations are almost negligible for offset values of up to 10um.
- Schemes with smaller lenses have greater sensitivity to displacement.

Tilt

Very high sensitivity



EBO Coupling - Plano-Convex Lenses | Lens Tilt



- For a tilt of 1º, coupling efficiency drops to -2.51, -2.37 and -3.00dB for lenses thickness for 0.75, 1.00 and 1.50mm, which represents variations of 0.91, 1.41, 2.45dB, respectively.
- Therefore, most limiting factor in an EBO coupler is the angle between the lenses. It must be limited to be bellow ±0.2º.
- Lenses with larger thicknesses are more sensitive to tilt variations.

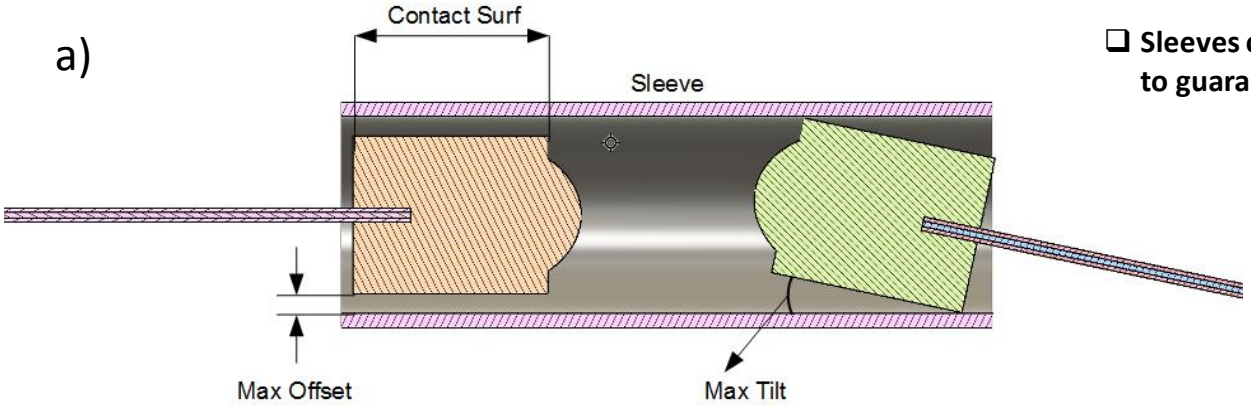
4. Sensitivity Analysis of EBO Connectors

Keeping the tilt tolerance bellow 0.2º is not a difficult task.

For example, if we consider an EBO connector with an alignment sleeve, like the one shown in Figure a), where:

- Lenses have contact surface of 6mm.
- Sleeve has an inner diameter tolerance of +20um (max offset of ±10um).
  - **Then, the maximum possible tilt would be 0.19º.**
- Maximum tilt depends on the alignment tolerance and the connector dimensions.

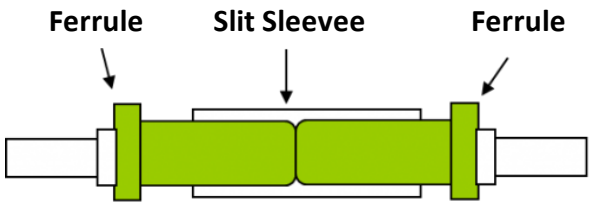
a)



Illustrative diagram, dimensions are not at scale

Slit sleeves

b)



- Slit sleeves are mostly used in Fiber Adapter for the main purpose of connecting and aligning two inserted Ferrules together.
- **Sleeves can also be implemented on EBO connectors to guarantee the fiber alignment and tilt.**

5 Ball Lens EBO Connector for MM Fibers:

- Ball lenses are widely used in VCSEL-to-Fiber and SM fiber-to-fiber coupling systems since they are:
  - Inexpensive,
  - Mechanically compact
  - Significantly simpler to mount, position, and align due to their complete rotational symmetry.
- However, ball lenses have less degrees of freedom, we can only vary the diameter of the lens and the material.
- While in a plane-convex lens we can vary the material, the thickness, the radius of curvature and even the coefficients of asphericity.

5. Ball Lens EBO Connector for MM fibers

a) Single mode Fiber-to-Fiber coupling using ball lenses

- ❑ Material = S-LAH79 (n=2): Expensive but it is required to get the fiber at 0mm from the lens surface.
- ❑ Working Distance = 0mm (also called Back Focal Length, BFL)
- ❑ Lens diameter = 1mm
- ❑ Coupling Efficiency = **-0.45dB**

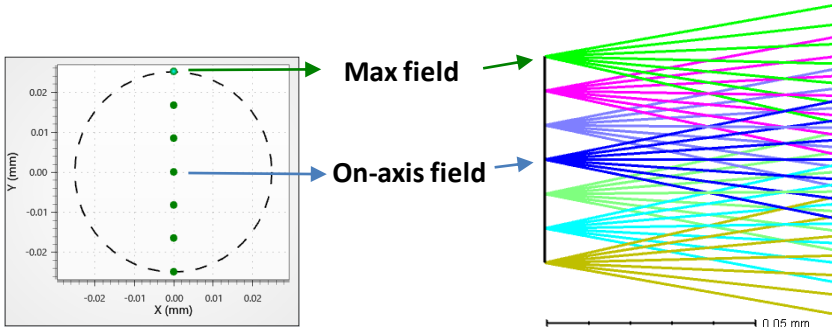
b) Considering a MM fiber of 50um core (same scheme of a)

- ❑ We find that it is not possible to have a good coupling efficiency with the fiber at the EFL of 0mm.
- ❑ In this case the efficiency drops to **-7dB**.

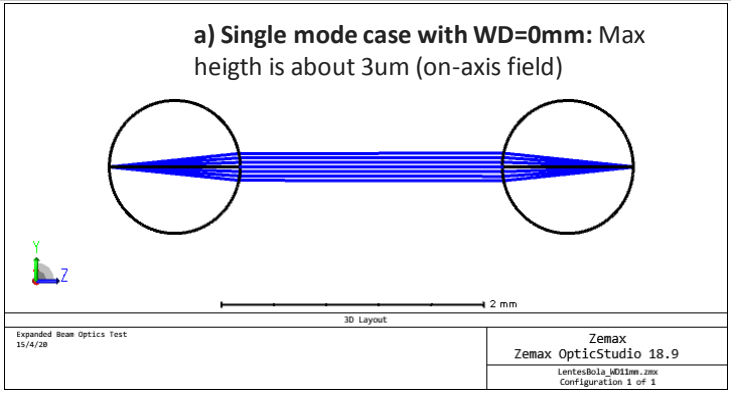
c) It is necessary to increase the WD if an MM fiber is used

- ❑ Coupling efficiency can be increased to **–1.1dB** by moving the fibers 0.236mm away from the lenses surfaces.
- ❑ The resulting beam is not well collimated, which increases the sensitivity of the system against possition tolerances.

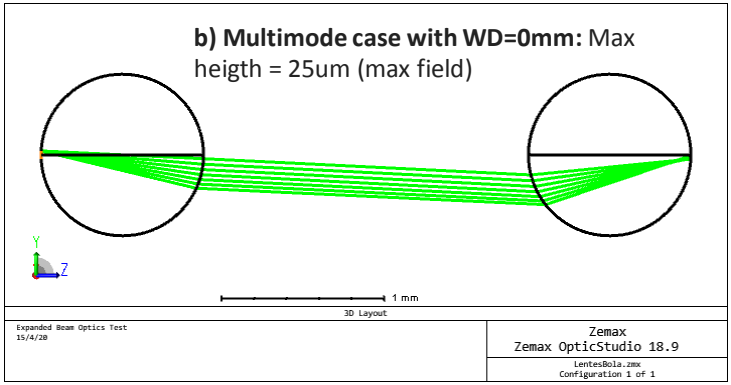
Fields of MM fiber Model



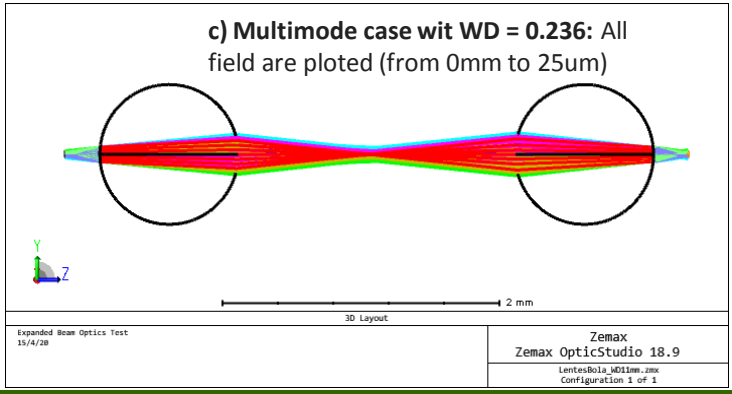
a) Single mode case with WD=0mm: Max heigth is about 3um (on-axis field)



b) Multimode case with WD=0mm: Max heigth = 25um (max field)

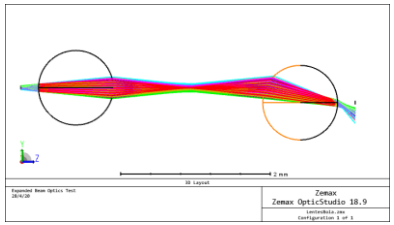


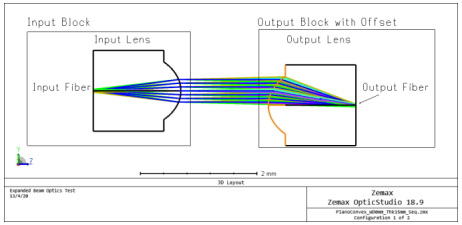
c) Multimode case wit WD = 0.236: All field are ploted (from 0mm to 25um)



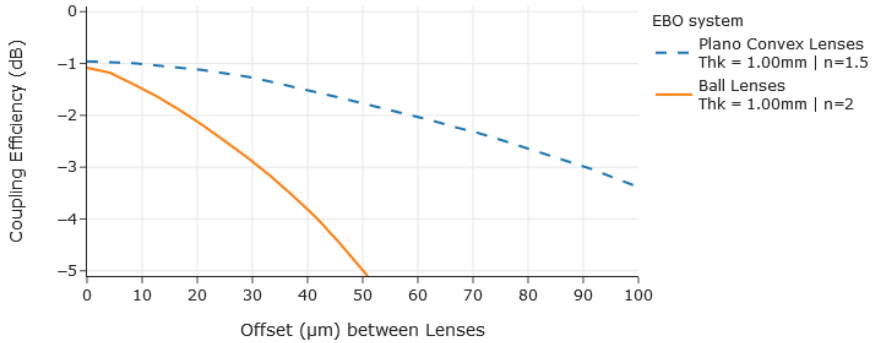
5. Ball Lens EBO Connector for MM fibers

Offset Sensitivity



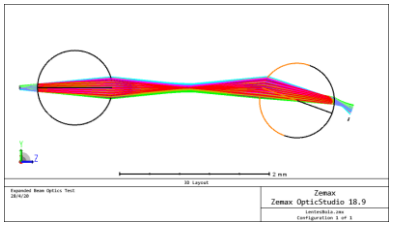


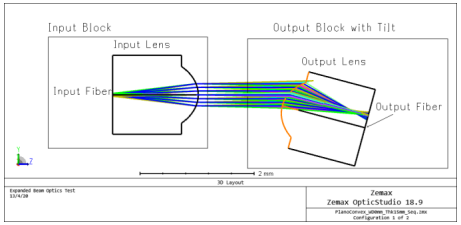
EBO Coupling - Plano-Convex Vs Ball | Offset Sensitivity



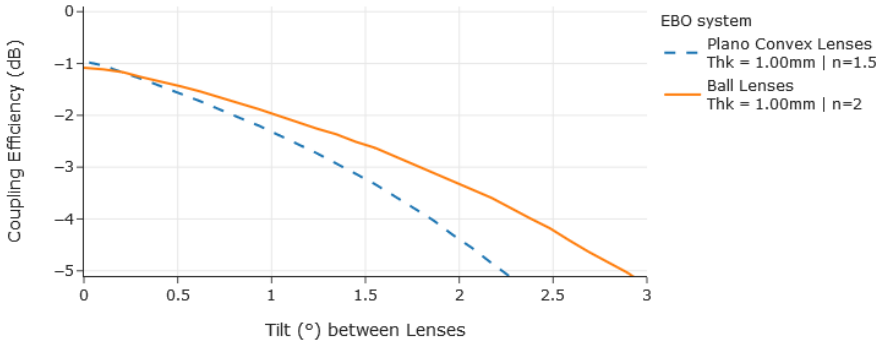
- ❑ The sensitivity to offset with ball lenses is higher because the beam is less collimated.
- ❑ The lack of collimation also adds sensitivity to the separation between the lenses.
- ❑ In addition, in the system with ball lenses, the distance between the fiber and the lens should also be controlled.

Tilt Sensitivity





EBO Coupling - Plano-Convex Vs Ball | Tilt Sensitivity

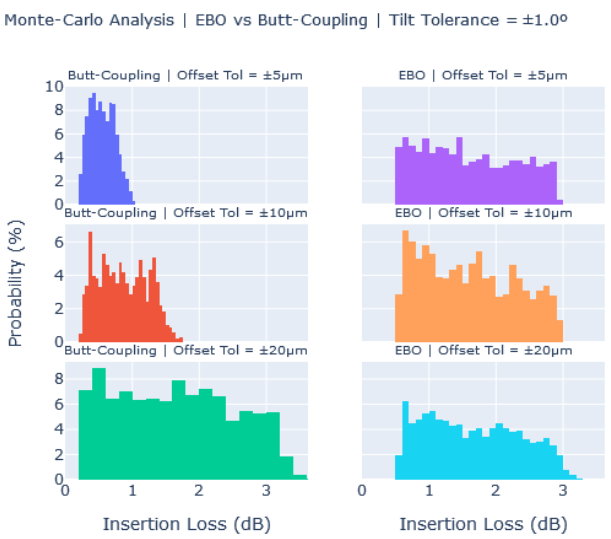


- ❑ On the other hand, if the beam is less collimated, the sensitivity to tilt decreases (as shown in the figure above).
- ❑ However, this improvement is very small in the range of interest (tilt less than 1º).

6 Discussion of results:

5. Discussion of Results: Monte-Carlo Analysis BC vs EBO

Tilt ±1º



BC EBO

Tilt ±0.5º

BC EBO

Tilt ±0.2º

BC EBO

EBO: Based on plano-convex lenses with thickness = 1mm, radius = 0.338mm, conic = -0.529 and n=1.51 (see slide 11 for scheme)

- **BC connectors:**
  - ✓ Lower tilt sensitivity than EBO connectors.
  - ✓ To keep maximum losses below 1dB, the offset tolerances (missalignement and gap) must be below ±5um.

- **EBO connectors:**
  - ✓ Lower offset sensitivity than BC connectors.
  - ✓ To keep maximum losses below 1dB, the tilt tolerances must be below ±0.2º, even with offset tolerances of up to ±20um.

7 Conclusions:

- BC and EVO tolerance requirements are opposite:
  - ✓ EBO is more sensitive to tilt variations.
  - ✓ BC is more sensitive to misalignments.
- EBO connectors have higher insertion losses than BC connectors under nominal conditions.
- Fiber diameter limits performance in EBO couplers based on Ball Lenses for MMFs.
- The choice of EBO or BC will depend on:
  - ✓ The manufacturing tolerances.
  - ✓ The required fiber density (EBO connectors are larger).
  - ✓ Of the environmental characteristics that the connector must resist.

Feasibility analysis of different optical connectivity technologies

Thank you !

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