Modal Noise vs Misalignment Losses in MMFs Connectors

Experimental Characterization

IEEE P802.3cz Multi-Gigabit Optical Automotive Ethernet Task Force, Jun. 2021.

Presented by:

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08. June, 2021
Rev 2.0

Modal Noise vs Misalignment Losses in MMFs Connectors

1. Objective

- ☐ **Demonstrate the relationship between insertion loss in multi-mode connectors and modal noise.**

2. Agenda

- ☐ **Modal Noise Estimation from RIN_{OMA} Measurements**
  - Definition of Modal Noise Estimation
- ☐ **Launching Setup: VCSEL to Fiber Coupling**
  - Modal Noise due to VCSEL to Lens Radial Misalignment
- ☐ **Modal Noise in Butt-Coupling (BC) Connections**
  - Effects of Radial Misalignment
  - Effects of Axial Misalignment
  - Effects of Tilt Misalignment
- ☐ **Modal Noise in Expanded Beam Optics (EBO) Connections**
  - Effects of Tilt Misalignment
    - Relation between Tilt Misalignment in EBO and Radial Misalignment in BC.
  - Analysis of Radial Offset in EBO
    - Relation between Radial Misalignment in EBO and Tilt Misalignment in BC.
- ☐ **Conclusions**

Modal Noise vs Misalignment Losses in MMFs Connectors

1. Modal Noise Estimation from $\mathrm{RIN}_{\mathrm{OMA}}$ Measurement

1. Modal Noise Estimation from $\mathrm{RIN}_{\mathrm{OMA}}$ Measurement

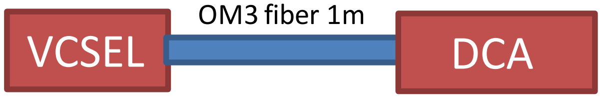
1. $\mathrm{RIN}_{\mathrm{OMA}}$

Test method for $\mathrm{RIN}_{\mathrm{OMA}}$ has been defined by [1] as:

$$RIN_{OMA} = 10 \times log_{10}\left(\frac{RN_{one} + RN_{zero}}{OMA^2 \times BW_N}\right)$$

where $\mathrm{RN}_{\mathrm{one/zero}}$ is standard deviation of noise measured in level 1/0 (in Watts); OMA is the optical modulation amplitude (in Watts) and BW_{N} is the noise equivalent bandwidth (in Hz).

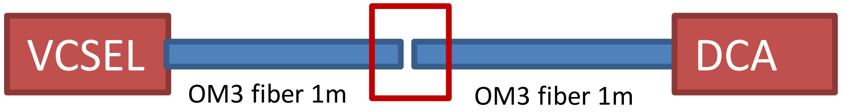
VCSEL's RIN can be considered to be the main source of noise in the following setup (setup 1):



- If the VCSEL is directly connected to the DCA with a short section of fiber and there is no mode selective loss in the VCSEL coupling.
- Scope (DCA) background noise is compensated.

2. Estimation of Modal Noise (MN)

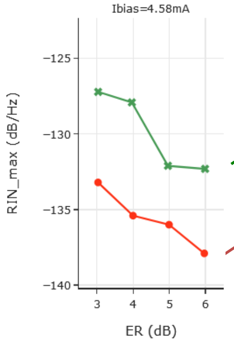
Setup 2:



If we consider a link with in-line connectors (**setup 2**), the $\mathrm{RIN}_{\mathrm{OMA}}$ measurements in the DCA will be effected by the Modal Noise (MN) that may be produced due misalignments in the connectors.

The difference of variances between the **Total Noise ($\mathrm{RIN}_{\mathrm{OMA,DUT}}$ from setup 2)** and the reference **$\mathrm{RIN}_{\mathrm{OMA}}$ (from setup 1)** will be an acceptable approximation of MN caused by the connectors misalignments. This can be calculated as:

$$\frac{\sigma_{n0,MN} + \sigma_{n1,MN}}{OMA} = \sqrt{\left(10^{\frac{RIN_{OMA,DUT}}{10}} - (10^{\frac{RIN_{OMA,REF}}{10}}\right) \times BW_n}$$



BC connection with radial offset (IL = 6dB): Total noise is $\mathrm{RIN}_{\mathrm{OMA,REF}}$ + MN = RINOMA,DUT.

BC connection without any offset: $\mathrm{RIN}_{\mathrm{OMA,REF}}$.

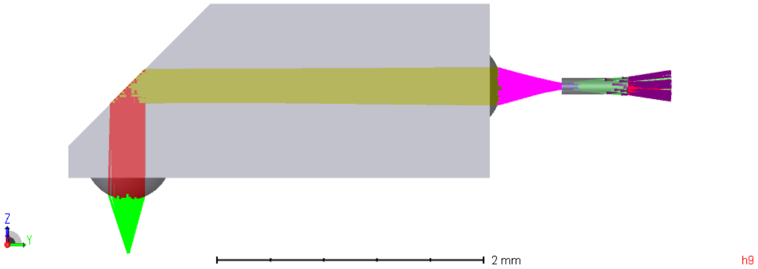
Modal Noise vs Misalignment Losses in MMFs Connectors

2. Launching Setup: VCSEL to Fiber Coupling

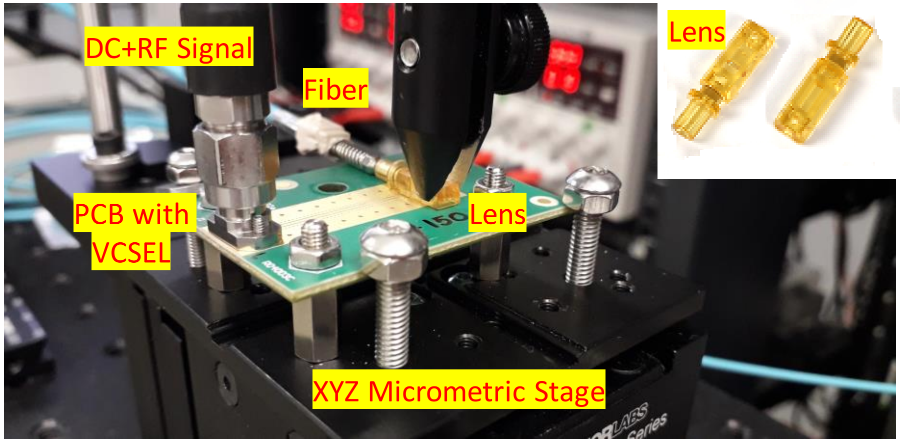
2.1. Launching Setup

1. COB Type Lens (ULTEM)

- ☐ Coupling Efficiency > 78% | IL < 1.1dB.
  - ➢ Losses are mainly due to material attenuation and Fresnel. **No mode selective loss.**

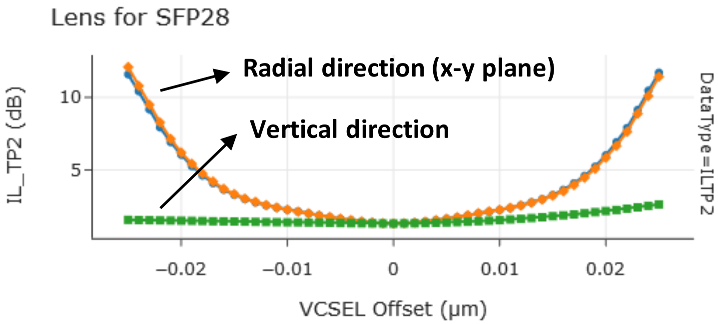


- ☐ **Experimental Setup: VCSEL (850nm) to Fiber Coupling.**

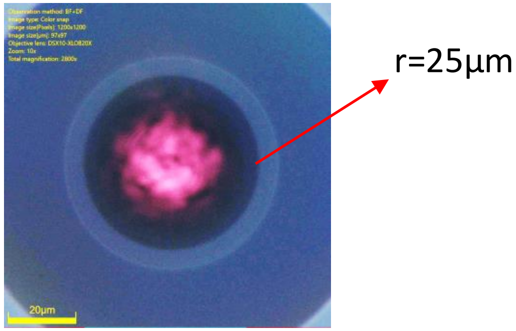


2. Alignment for the lowest RIN

- ☐ IL vs VCSEL Offset (**Simulation**).

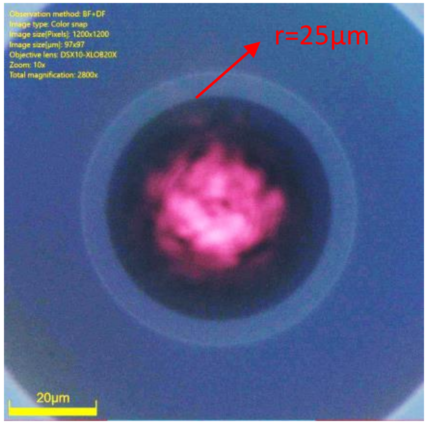


- ☐ **NFP at TP2 (1m of fiber). Underfilled launch!**
  - ➢ To avoid selective losses at the VCSEL-to-Fiber coupling in order to evaluate the modal noise in the intermediate connectors.



2.2. Effects of VCSEL-to-Lens Radial Misalignment

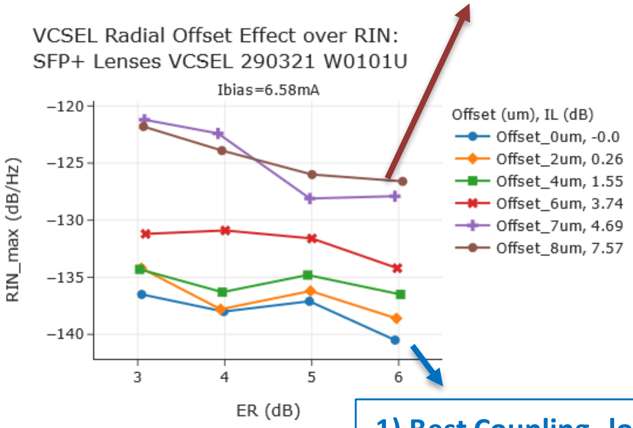
- **1. Reference RIN ($RIN_{OMA,REF}$)**
  Best Coupling, No misalignment.



1. Degradation of RIN_{OMA} Measurements

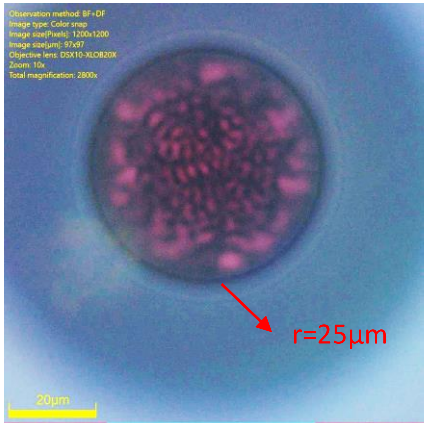
- Losses due to VCSEL-to-Lens Misalignment generates Noise.
- Mode Selective Loss

2) Bad Coupling, highest RIN.


VCSEL Radial Offset Effect over RIN:
SFP+ Lenses VCSEL 290321 W0101U

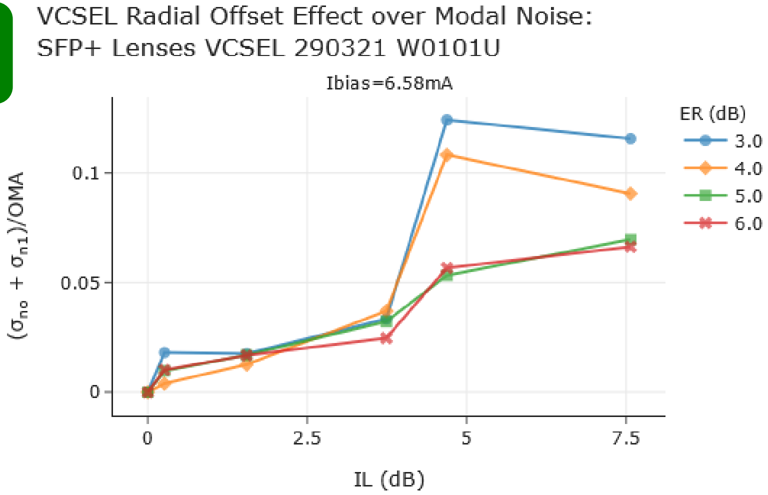
1) Best Coupling, lowest RIN.

- **2) Worst $RIN_{OMA,DUT}$**
  Worst Coupling, highest misalignment



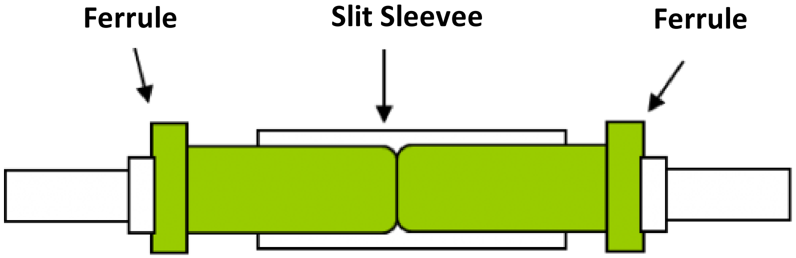
2. Estimation of Modal Noise

- Modal Noise is estimated from $RIN_{OMA,DUT}$.
- There is a direct relationship between ILs due to VCSEL-to-Lens radial misalignment and Modal Noise


VCSEL Radial Offset Effect over Modal Noise:
SFP+ Lenses VCSEL 290321 W0101U

Modal Noise vs Misalignment Losses in MMFs Connectors

3. Modal Noise in Butt-Coupling Connections

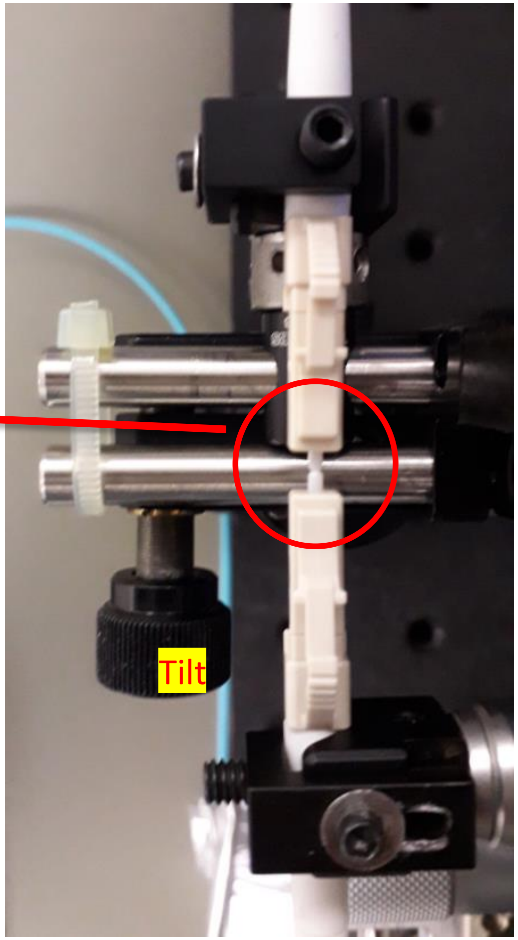


3.1. Modal Noise in Butt-Coupling

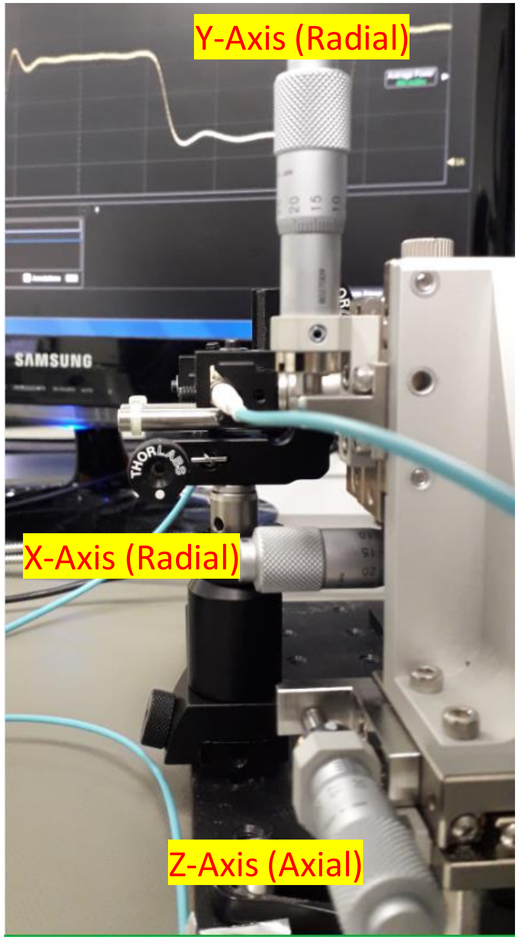
1. Experimental Setup

- IL < 0.55dB
- No spring-loaded
- 2 x LC fibers of 2m with PC termination
- No mandrel wrapping

Tilt Control



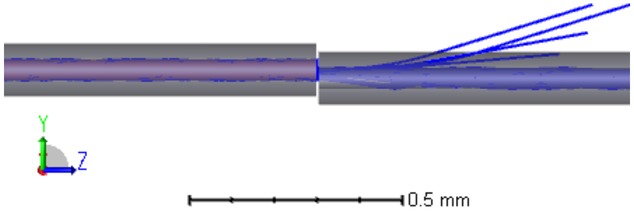
XYZ Control

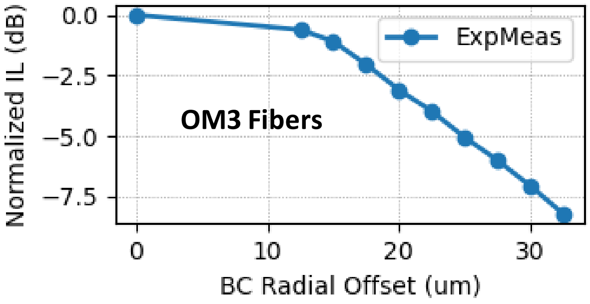


3.2. Modal Noise in Butt-Coupling: Effects of Radial Misalignments

BC: Radial Misalignment

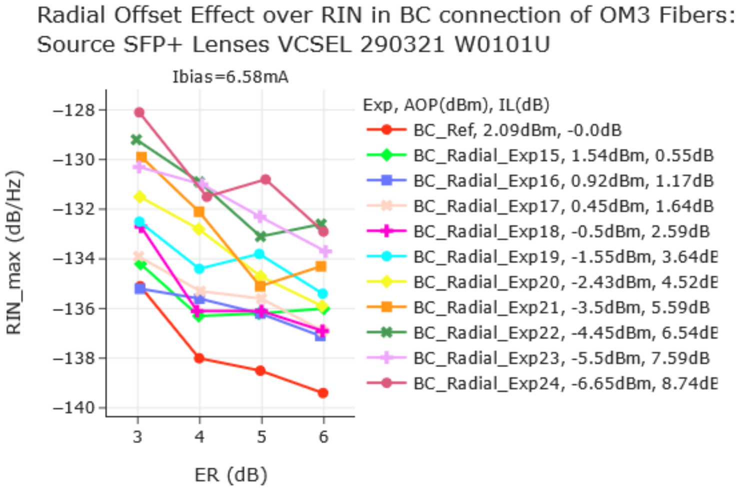
- IL with no offset = 0.55dB.
  - A small gap is needed between the fibers to allow radial displacement .
- **High sensitivity to Radial Misalignment.**
- **Direct dependence between MN and ILs.**





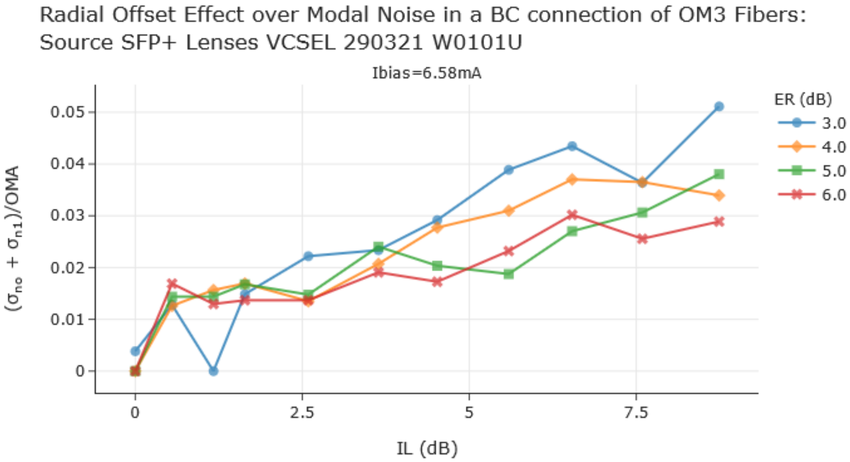
1. RIN_{OMA} Measurements

- Ref RIN_{OMA} measurement has been taken with a LC-to-LC connector.



Radial Offset Effect over RIN in BC connection of OM3 Fibers: Source SFP+ Lenses VCSEL 290321 W0101U

2. Estimation of Modal Noise

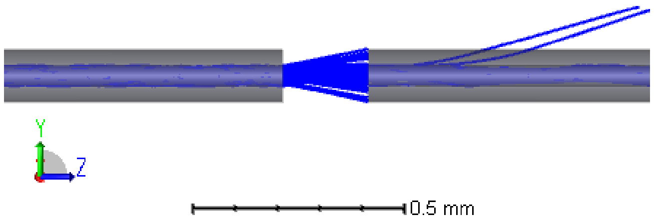


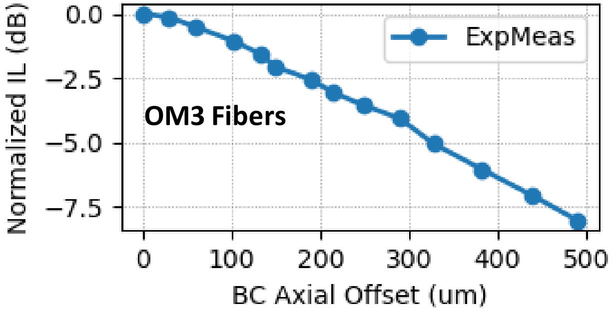
Radial Offset Effect over Modal Noise in a BC connection of OM3 Fibers: Source SFP+ Lenses VCSEL 290321 W0101U

3.3. Modal Noise in Butt-Coupling: Effects of Axial Misalignments

BC: Axial Misalignment (Gap)

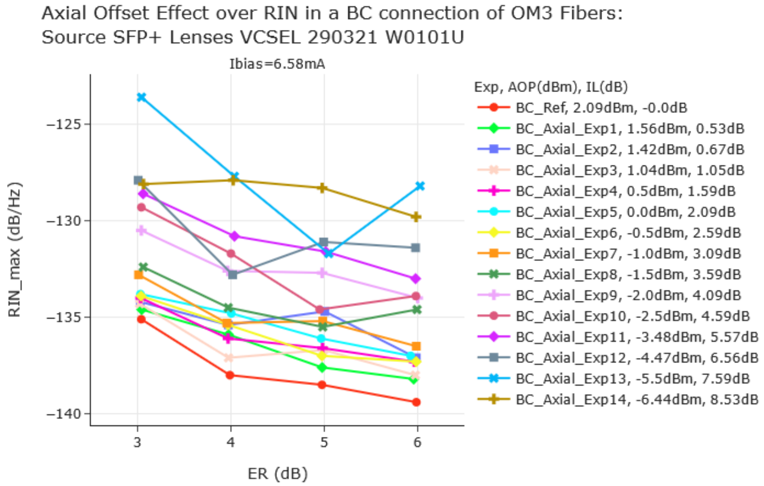
- IL with no offset = 0.53dB
- IL has **low dependence with the gap**, especially if manufacturing tolerances are taken into account. However, any gap generates reflections.
- **Direct dependence between MN and ILs.**
  - Quite similar to the case of radial misalignment



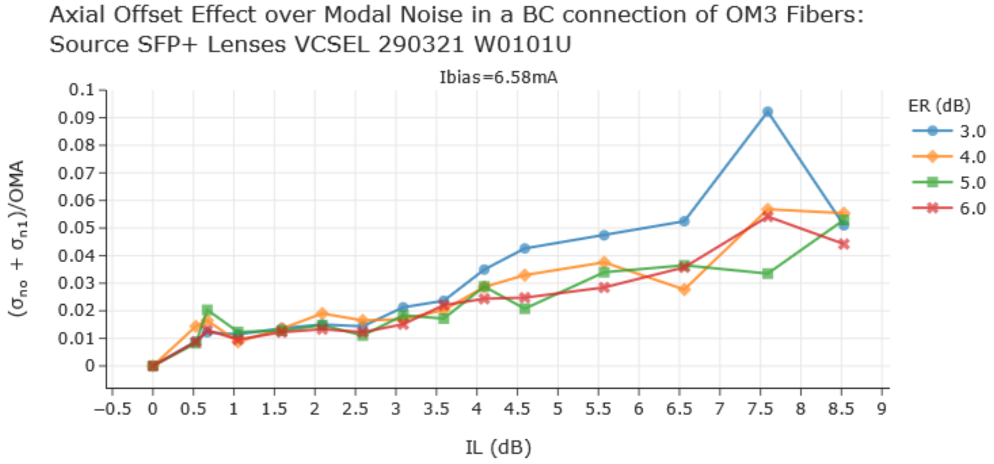


1. $\mathrm{RIN}_{\mathrm{OMA}}$ Measurements

- Ref $\mathrm{RIN}_{\mathrm{OMA}}$ measurement has been taken with a LC-to-LC connector.



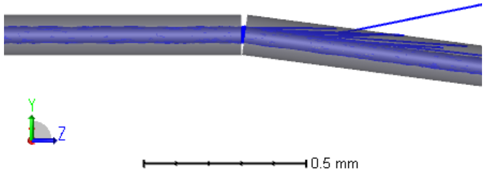
2. Estimation of Modal Noise

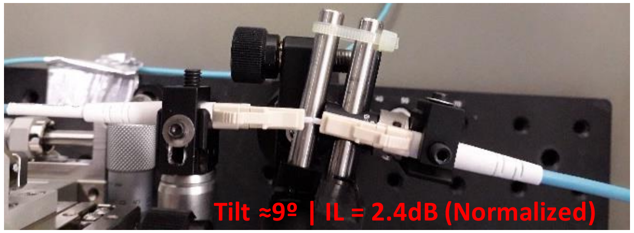


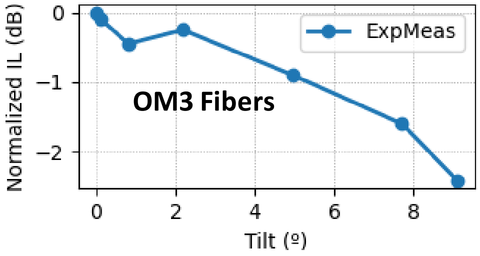
3.4. Modal Noise in Butt-Coupling: Effects of Tilt Misalignments

BC: Tilt Misalignment

- ☐ IL with no offset = 0.55dB
- ☐ BC has Very low sensitivity to tilt.
  - However, it is not a realistic case.
  - It is not possible to have very high tilt values in a connector.
- ☐ There is a direct relationship between MN and IL from IL> 1dB.

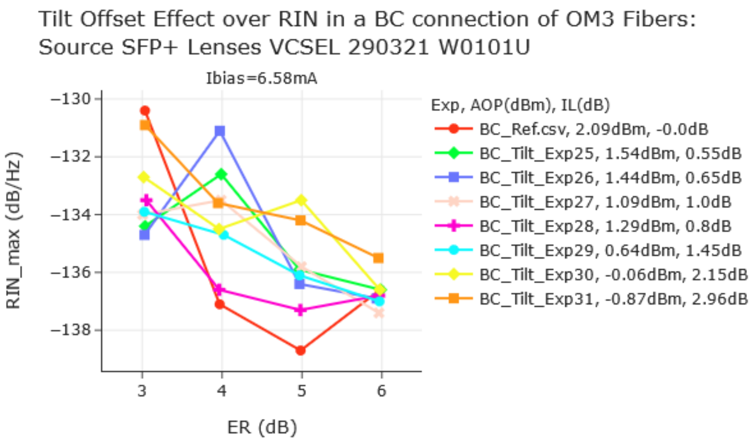




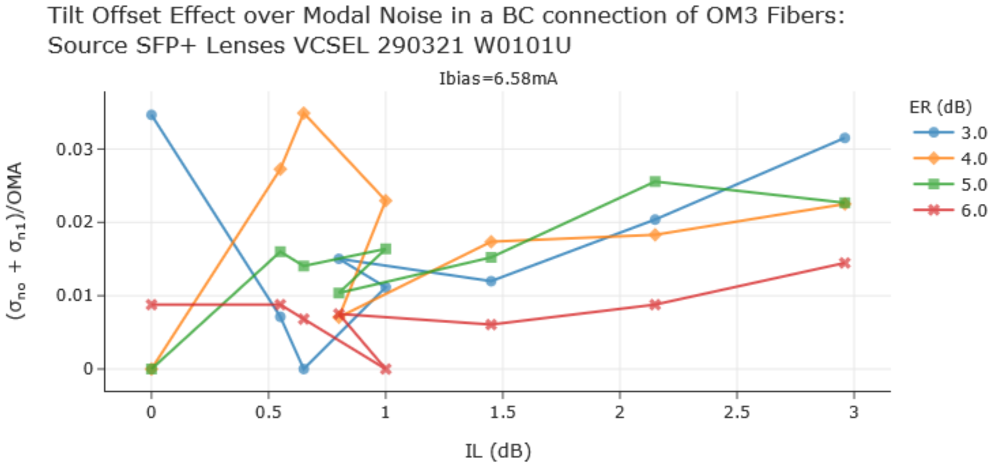


1. RIN$_{OMA}$ Measurements

- ➢ Ref RIN$_{OMA}$ measurement has been taken with a LC-to-LC connector.

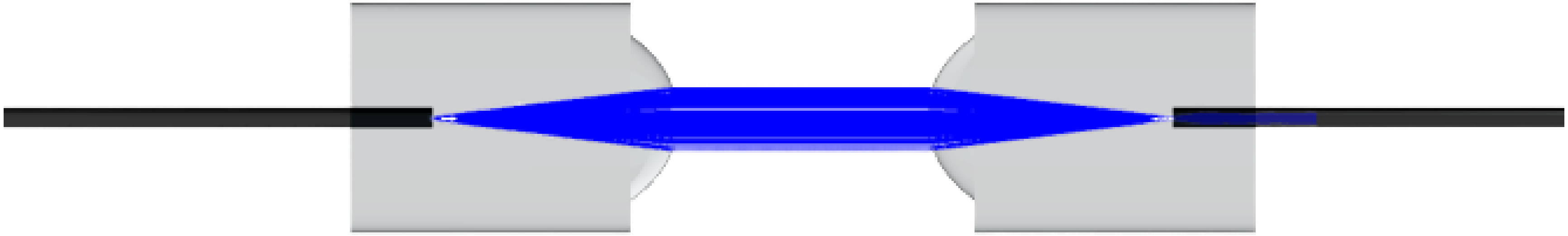

Tilt Offset Effect over RIN in a BC connection of OM3 Fibers: Source SFP+ Lenses VCSEL 290321 W0101U

2. Estimation of Modal Noise


Tilt Offset Effect over Modal Noise in a BC connection of OM3 Fibers: Source SFP+ Lenses VCSEL 290321 W0101U

Modal Noise vs Misalignment Losses in MMFs Connectors

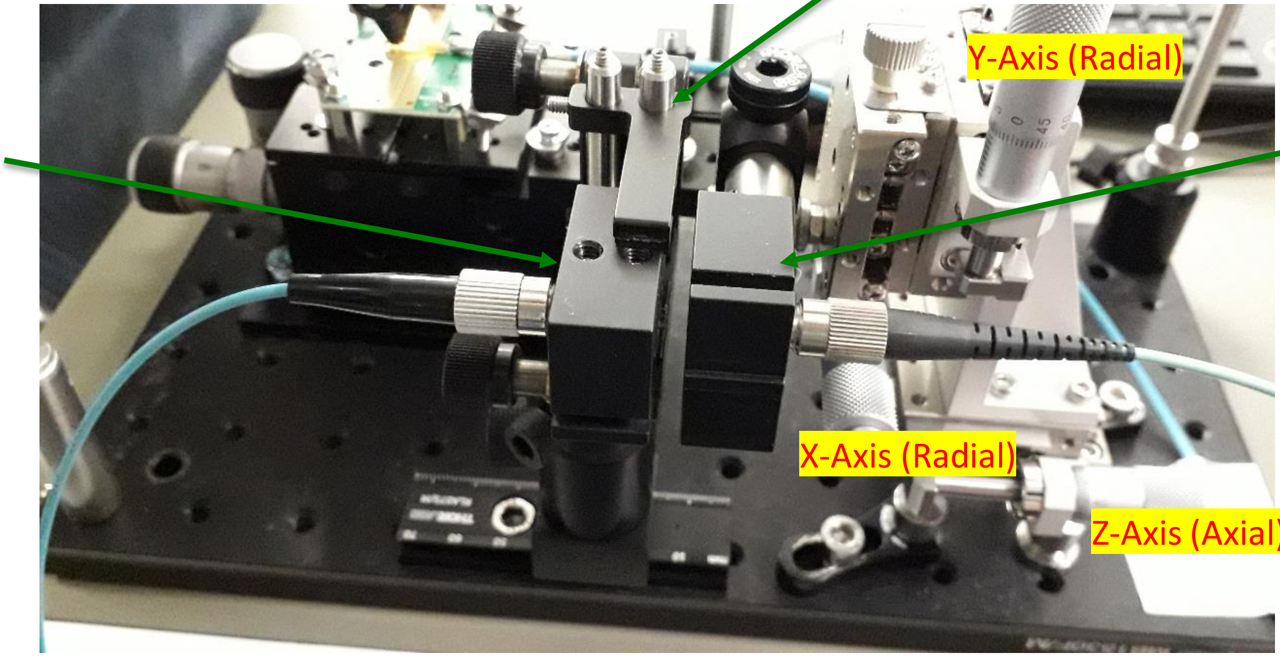
4. Modal Noise in Expanded Beam Optics (EBO) Connections



4. Modal Noise in Expanded Beam Optics (EBO)

1. Experimental Setup

- Two 2m OM3 fibers. No mandrel wrapping.
- EBO connector with two collimators: F220FC-850
  - **Beam diameter: 2.5mm**
  - **Focal distance: 11.12mm**
- Kinematic stage for **tilt** control: KM100C
  - **8mrad** Tilt per **turn** (from datasheet)
- **xyz** stage form alignment
- **Min IL = 0.45dB**



4. Modal Noise in EBO: Experimental Tilt Measurements

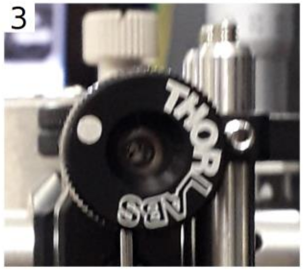
Tilt Measurements

- ❑ AOP Measurements
  - ➢ OPTOKON 820
    - ▪ 1mm diameter detector
  - ➢ Micrometer Head
    - ▪ Tilt = 0.46º (8mrad) per turn (from datasheet)

Image	Tilt_Deg	AOP_dBm	IL_dB
1	0	-1.46	0
2	0.0336125	-2	0.54
3	0.0503942	-2.5	1.04
4	0.0641543	-3	1.54
5	0.0790596	-3.61	2.15
6	0.0956225	-4.5	3.04
7	0.1113365	-5.6	4.14
8	0.1407354	-7.6	6.14
9	0.1565097	-9.5	8.04
10	0.1742315	-11.31	9.85


1


2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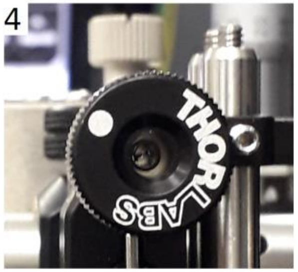
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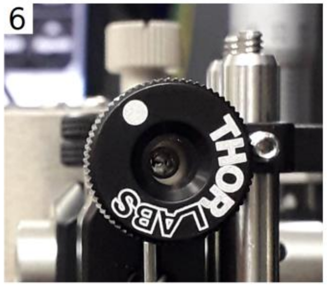
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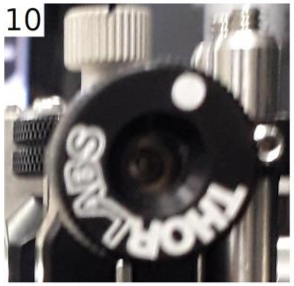
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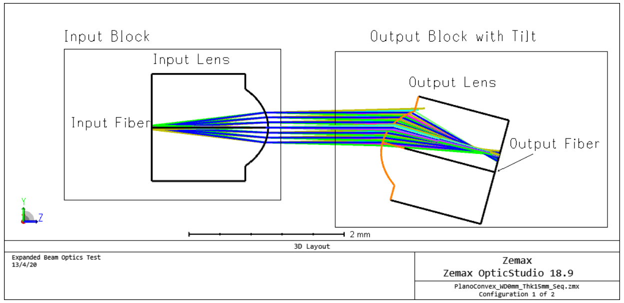
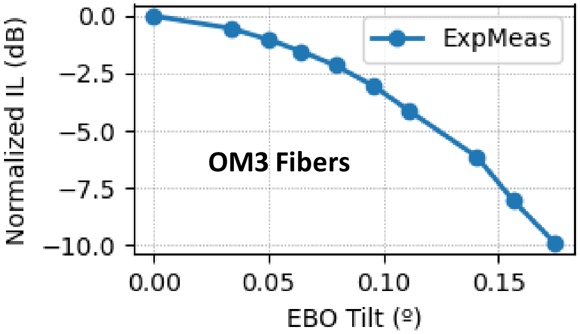
4. Modal Noise in EBO: Effects of Tilt Misalignment

EBO: Tilt Misalignment

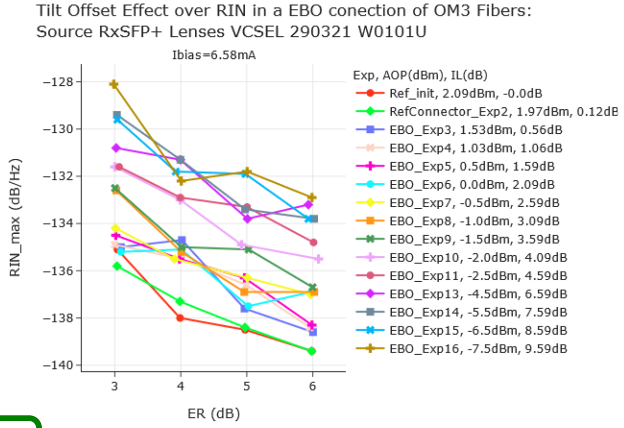
- ☐ IL with no offset = 0.56dB.
- ☐ Fibers and collimators move as a single element .
- ☐ **High sensitivity to tilt.**
- ☐ **There is a direct relationship between ILs due to tilt and the modal noise.**
- ☐ **Tilt in EBO is equivalent to Radial Misalignment in BC.**



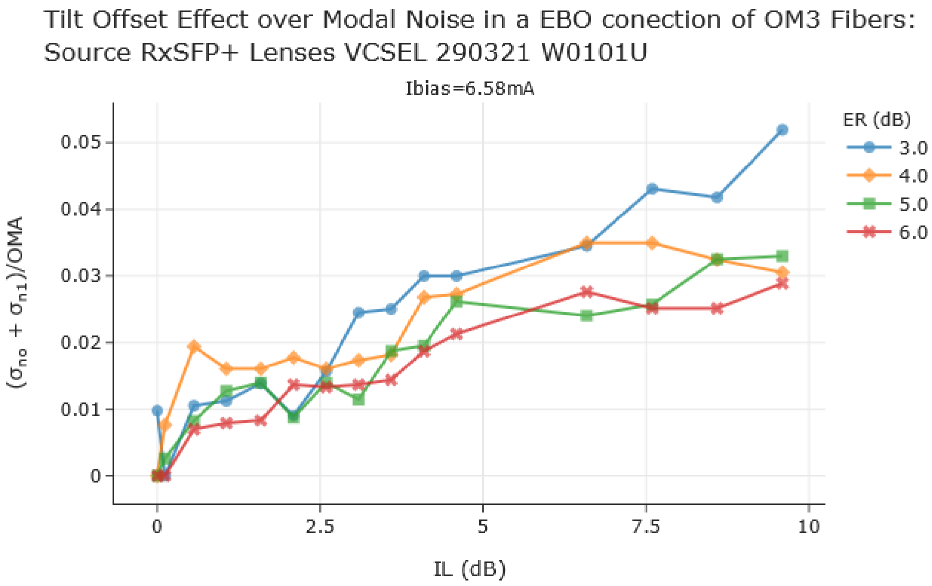


1. RIN$_{OMA}$ Measurements

- ➢ Ref RIN$_{OMA}$ measurement has been taken with a LC-to-LC connector.



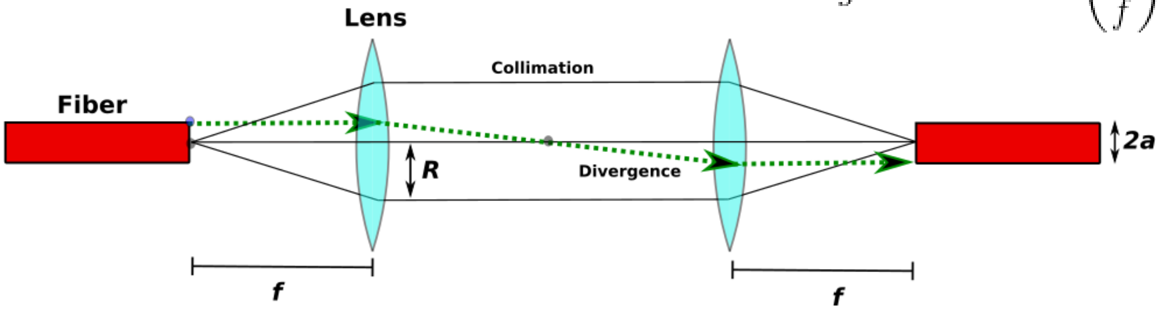
2. Estimation of Modal Noise



4. Modal Noise in EBO: Analysis of Tilt Misalignment

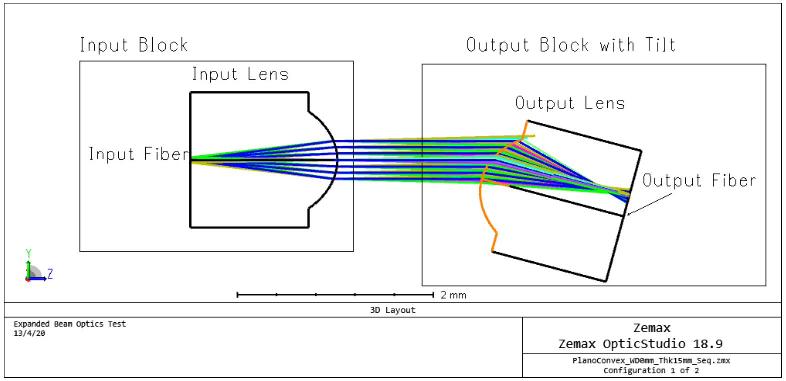
1. Tilt in EBO is equivalent to Radial Misalignment in BC

1.1. EBO: Basic ray diagram



$$Divergence = \arctan\left(\frac{a}{f}\right)$$

1.2. Divergence can be considered as tilt in EBO



3D Layout

Expanded Beam Optics Test
13/4/20

Zemax
Zemax OpticStudio 18.9

PlanoConvex_WD0mm_Thk15mm_Seq.zmx
Configuration 1 of 2

$$Tilt = arctan\left(\frac{\Delta r}{f}\right)$$

$$\Delta r : Radial\,Misalignment$$

$$\Delta r = f \times \tan\left(Tilt\right)$$

1.3. Verification

☐ Slide 16:

- In EBO the IL = 3.1dB when **Tilt = 0.096º.**
- In an EBO system with f = 11.12mm, a tilt of 0.096º generates an equivalent **Δr = 19µm** at the fiber input **(Theoretical value).**

Slide 10:

- In BC IL = 3.1dB when **Δr=20µm (Experimental value).**

4. Modal Noise in EBO: Analysis of Radial Misalignment

Radial Misalignment in EBO is equivalent to Tilt in BC

Simulation: Example of 500um radial offset (Paraxial Lenses | f = 5mm)

$$R = f \times tan(\theta_{max})$$

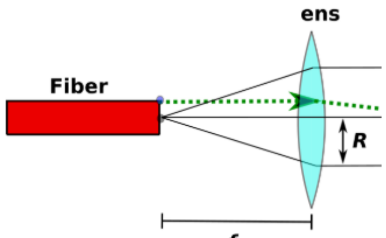


Figure 3: Relation between beam diameter and emission angle.

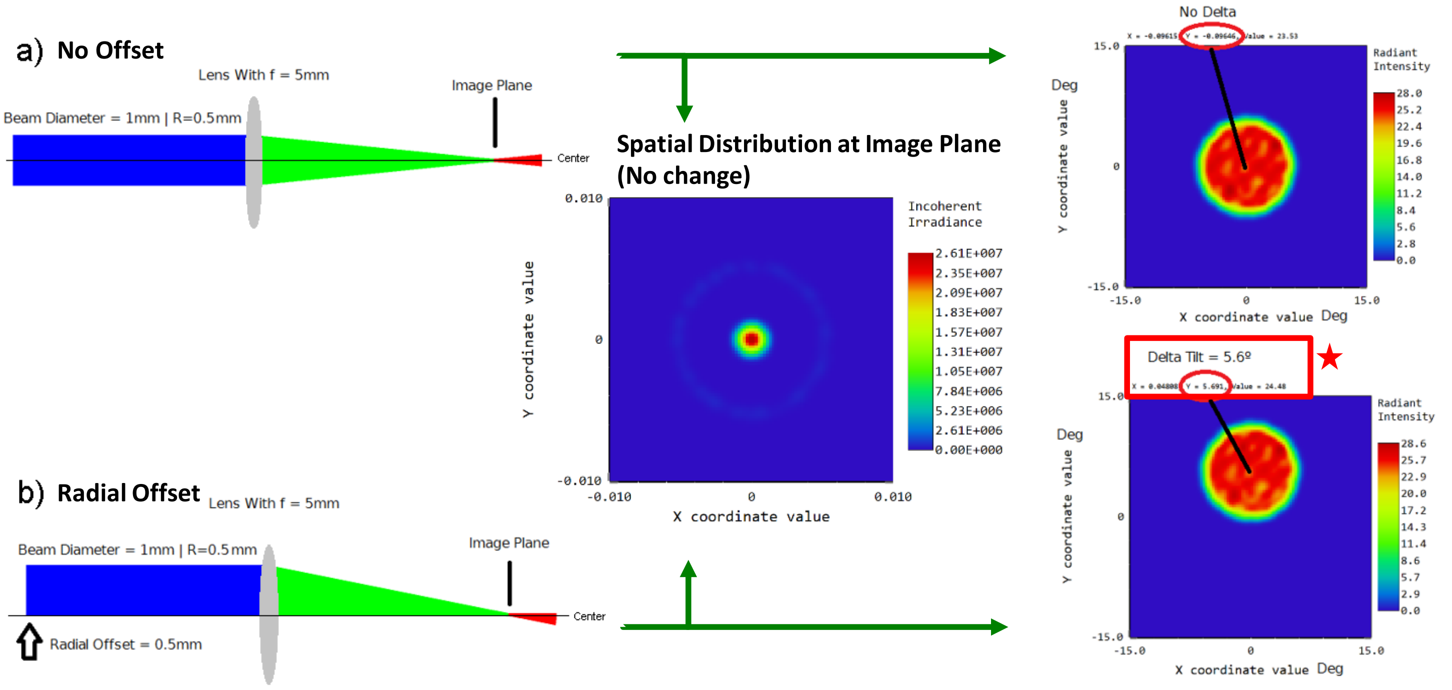
$$R + \Delta R = f \times tan(\theta_{max} + \Delta_\theta)$$

$$arctan\left(\frac{R+\Delta R}{f}\right) = \theta_{max} + \Delta_\theta$$

$$\Delta_\theta = arctan\left(\frac{R+\Delta R}{f}\right) - \theta_{max}$$

$$\boxed{\Delta_\theta = arctan\left(\frac{R+\Delta R}{f}\right) - arctan\left(\frac{R}{f}\right)}$$

An approximation! GI Profile has to be taken in to account.



In this example:

$$\Delta_\theta = arctan\left(\frac{0.5mm+0.5mm}{5mm}\right) - arctan\left(\frac{0.5mm}{5mm}\right) \boxed{= 5.6^\circ}$$ ★

- ☐ **EBO has very low sensitivity to radial misalignment.**
  - Values are far from a practical case (real connector).
- ☐ **This is because radial misalignment in EBO is equivalent to Tilt in BC.**

Modal Noise vs Misalignment Losses in MMFs Connectors

5. Conclusions:

5. Conclusions: Modal Noise vs Misalignment Losses in MMFs Connectors

Conclusions

- ☐ **It has been shown that there is a direct dependence between Insertion Losses due to Misalignments in BC and EBO connectors with the Modal Noise.**
    - ➢ Therefore, it is very important to take into account that the losses in the connectors not only reduce the power in the Rx but may also increase the noise.
- ☐ **On the other hand, it is important to remember that those losses that affect all modes equally (for example, material attenuation, Fresnel, NDFs) do not generate MSL and therefore do not generate modal noise.**
- ☐ **It has been shown that tilt misalignment in an EBO connector produces an effect equivalent to radial displacement in BC.**
    - ➢ BC is very sensitive to radial misalignment.
    - ➢ EBO is very sensitive to tilt misalignment.
    - ➢ Both effects can be related with a simple expression.
- ☐ **It also has been shown that radial misalignment in EBO produces an effect equivalent to a tilt misalignment in BC.**
    - ➢ BC is very robust to tilt misalignment.
    - ➢ EBO is very robust to radial misalignment.
    - ➢ Both effects can be easily related.
- ☐ **Therefore, the manufacturing tolerances EBO and BC connectors will be very similar.**
    - ➢ However, it is important to remember that EBO is much more resistant to contamination than BC.

5. Conclusions: Modal Noise vs Misalignment Losses in MMFs Connectors

Future work

- ☐ Measure **modal noise** due to misalignment on **multiple connectors.**
- ☐ **Improve** modal noise **measurements** by directly using the standard deviation components for high and low levels reported by the DCA.
- ☐ Determine the **relationship** between the **spectral width of** the VCSEL and the **modal noise** at the connectors.
- ☐ Determine **the influence of reflections** in multimode connectors over the modal noise.
- ☐ Repeat the measurements with a VCSELs at 980nm .

Modal Noise vs Misalignment Losses in MMFs Connectors

6. References:

1. R. Aranda and P.J. Pinzón, “*Test methods for VCSEL characterization*”, IEEE P802.3cz Multi-Gigabit Optical Automotive Ethernet Task Force, Jul. 2020. [Online]. Available: https://www.ieee802.org/3/cz/public/jul_2020/perezaranda_OMEGA_01b_0720_VCSEL_test_methods.pdf. [Accessed May. 25, 2021].