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Traceable Encircled Flux measurements for multimode fibre components and systems

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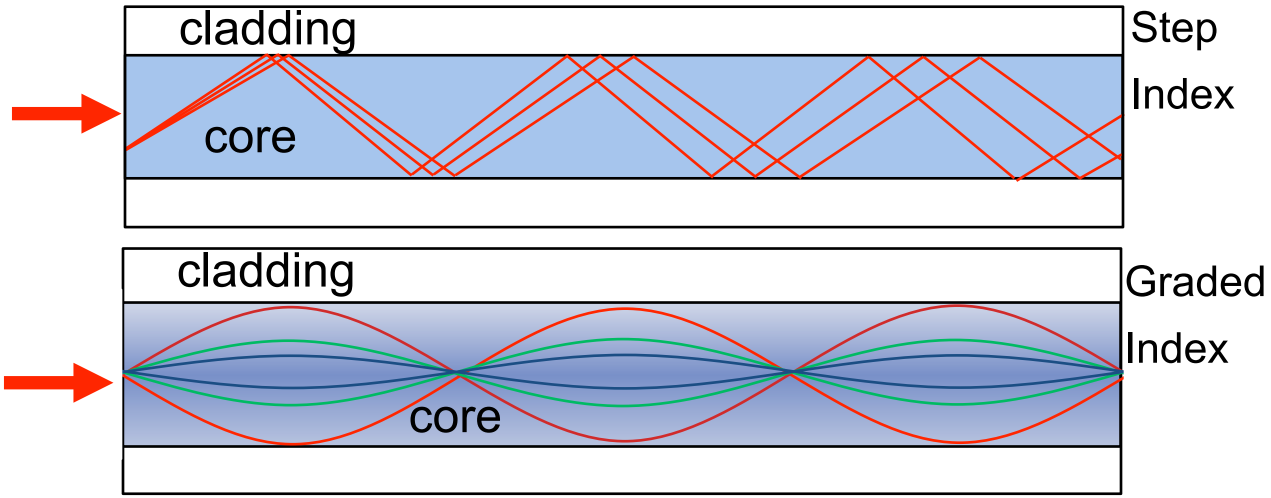
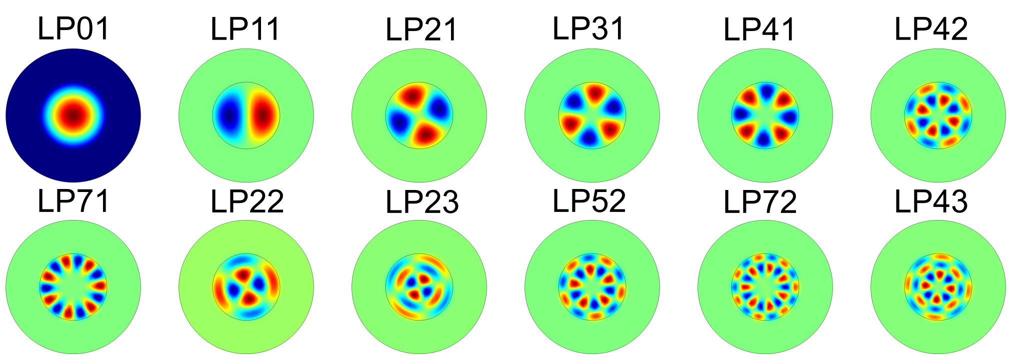
Outline

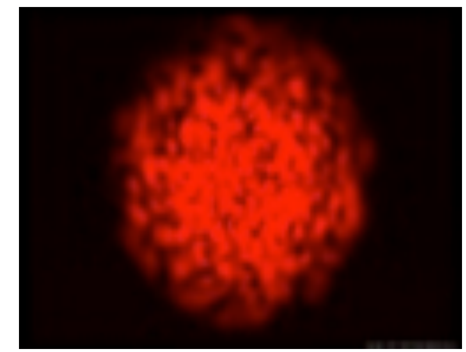
1. Introduction to the problematic of multimode fibres
2. The different metrics for modal distribution (MPD, CPR, EF)
3. Traceable Encircled Flux measurements
4. Limitations of the EF model
5. Normative aspects
6. Summary and conclusions

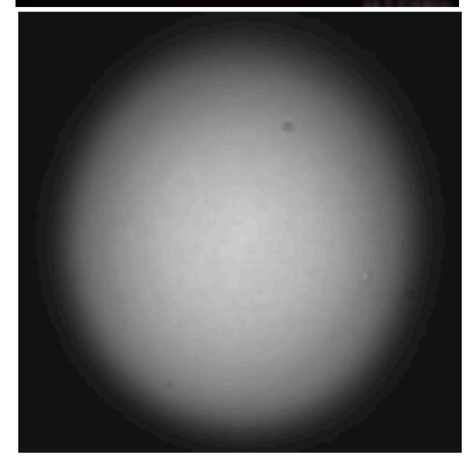
Introduction to the problematic of multimode waveguides

- Large number of guided modes
- Typically N > 2700 in a standard 50/125 fibre





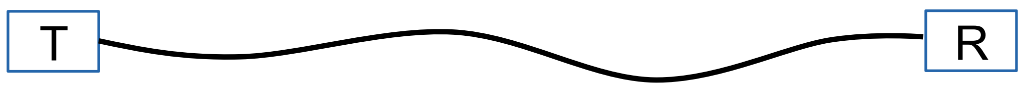




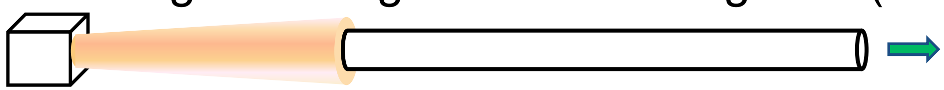
- Superposition of all guided modes lead to complex intensity patterns, depending on fibre and source properties

Modes in Multimode fibres

- The effective number of excited modes and their relative power distribution depend on how light is coupled into the fibre (beam size, divergence, alignment)
- The total attenuation and dispersion in a multimode fibre link depend on how light is coupled into the fibre, since the propagation properties of each mode is different



LED: large emitting area and divergence (Lambertian source)

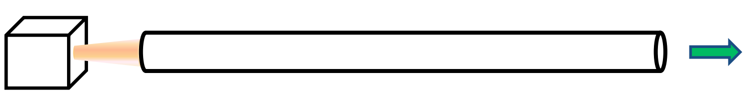


Overfill

Laser diode : single elliptical transverse mode, small beam waist

Underfill

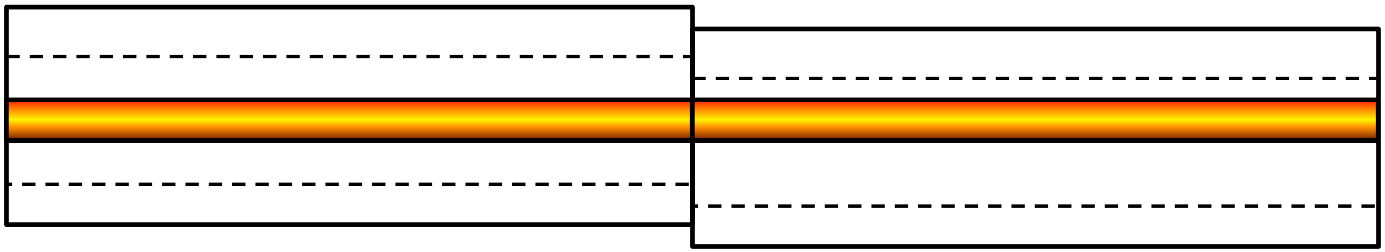
VCSEL: single circular transverse mode, larger beam waist



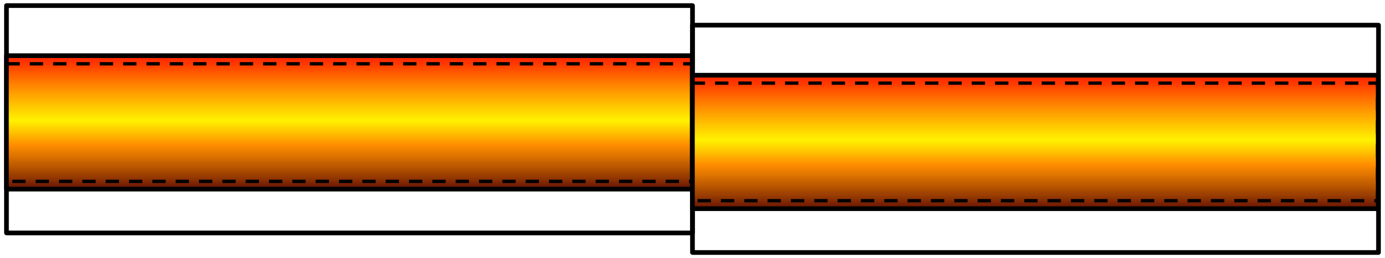
Underfill

Mode filling and coupling losses

- Underfill: no insertion loss observed, despite of the lateral misalignment of the two fibers



- Overfill:large sensitivity of the coupling losses to lateral misalignment

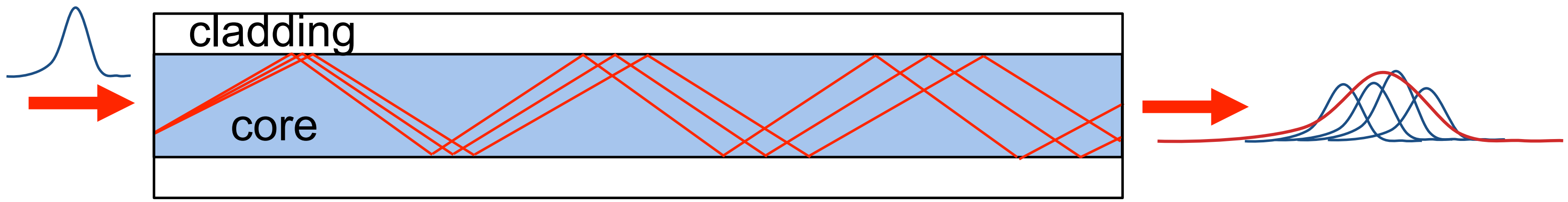


- Deviations in attenuation measurements > 50 % observed between extreme cases
- Comparable measurements in multimode fibre optics systems and components are only possible if the light distribution in the different available modes (modal distribution) is controlled and quantified.

Mode filling and bandwidth

- An incoming light pulse will simultaneously propagate in many different modes, which do not have all the same effective group index of refraction

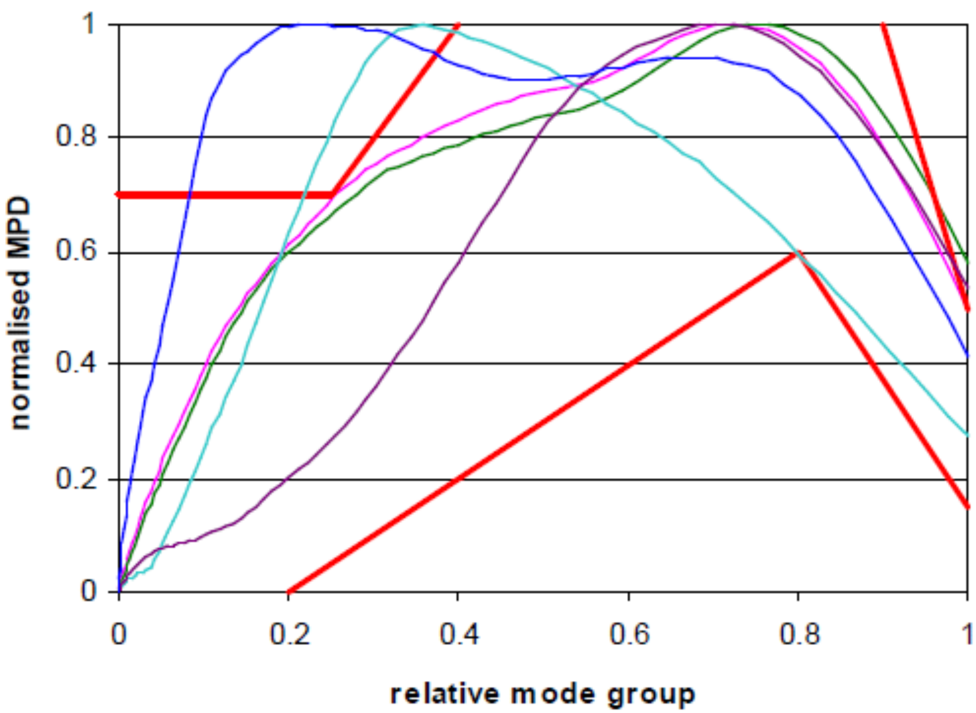
=> Pulse spreading(Intermodal dispersion), depending on the relative mode filling



	λ (nm)	Fiber Type OM4	OM3	OM2
Bandwidth (MHz·km) (Overfill)	850 nm	≥ 3500	Up to ≥ 2500	Up to ≥ 1000
Effective modal bandwidth (MHz·km) (restricted launch)	850 nm	≥ 4700	Up to ≥ 4000	Up to ≥ 1500

Metrics for Modal Distribution

- Modal Power Distribution (MPD)
  - Measurement of the far field intensity profile at the output of the multimode fibre, and computing of the relative intensity carried in each group number M_g of all contributing LP_{nm} modes. Each mode group number is defined by $M_g = 2m+n-1$.

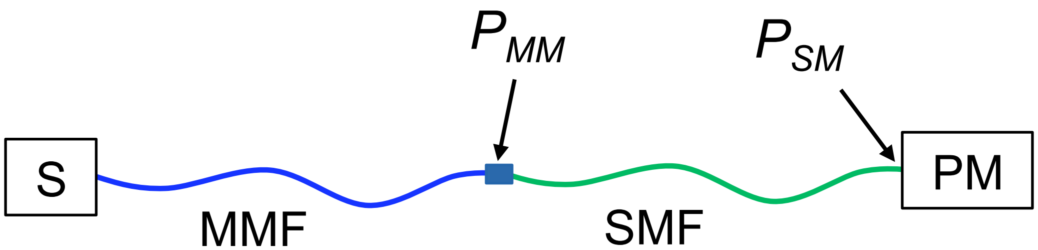


- Mode group number

Ensemble of modes having same
- Propagation constant
- Polarization
- Azimuthal angle

Metrics for Modal Distribution

- Coupled Power ratio (CPR)



$$CPR = 10*\log(P_{SM} / P_{MM})$$

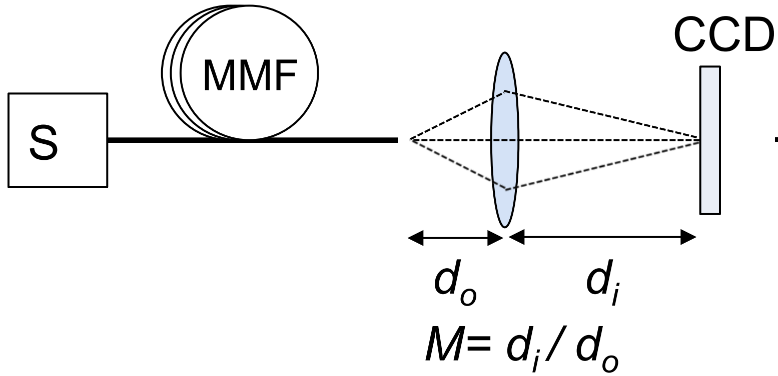
  - Allows to calculate a rough estimate of the amount of power, which is guided close to the fibre core centre

➢ Both the MPD and the CPR methods do not deliver enough details of the modal distribution in order to define suitable templates for comparable loss measurement at the required level of accuracy

Measuring the modal distribution

Encircled Flux (*EF*)

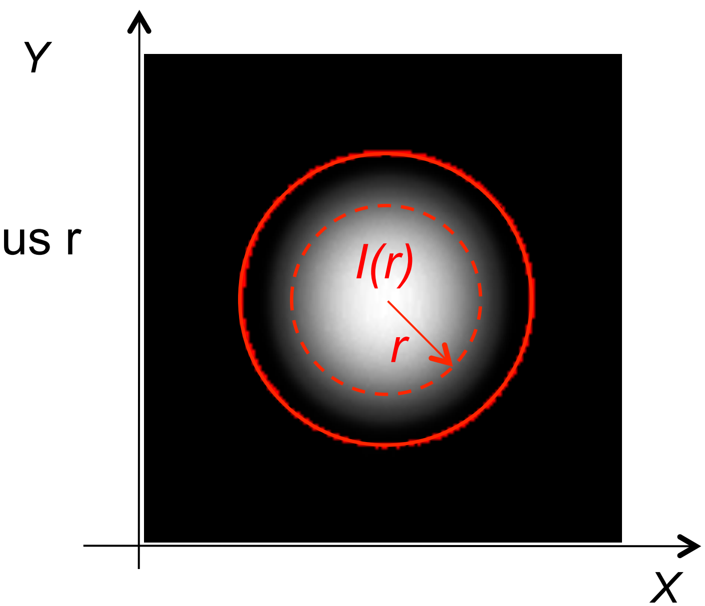
- Determination of the radial distribution of the light intensity at the output of the fibre (near field)



$$I(x,y) \rightarrow I(r)$$

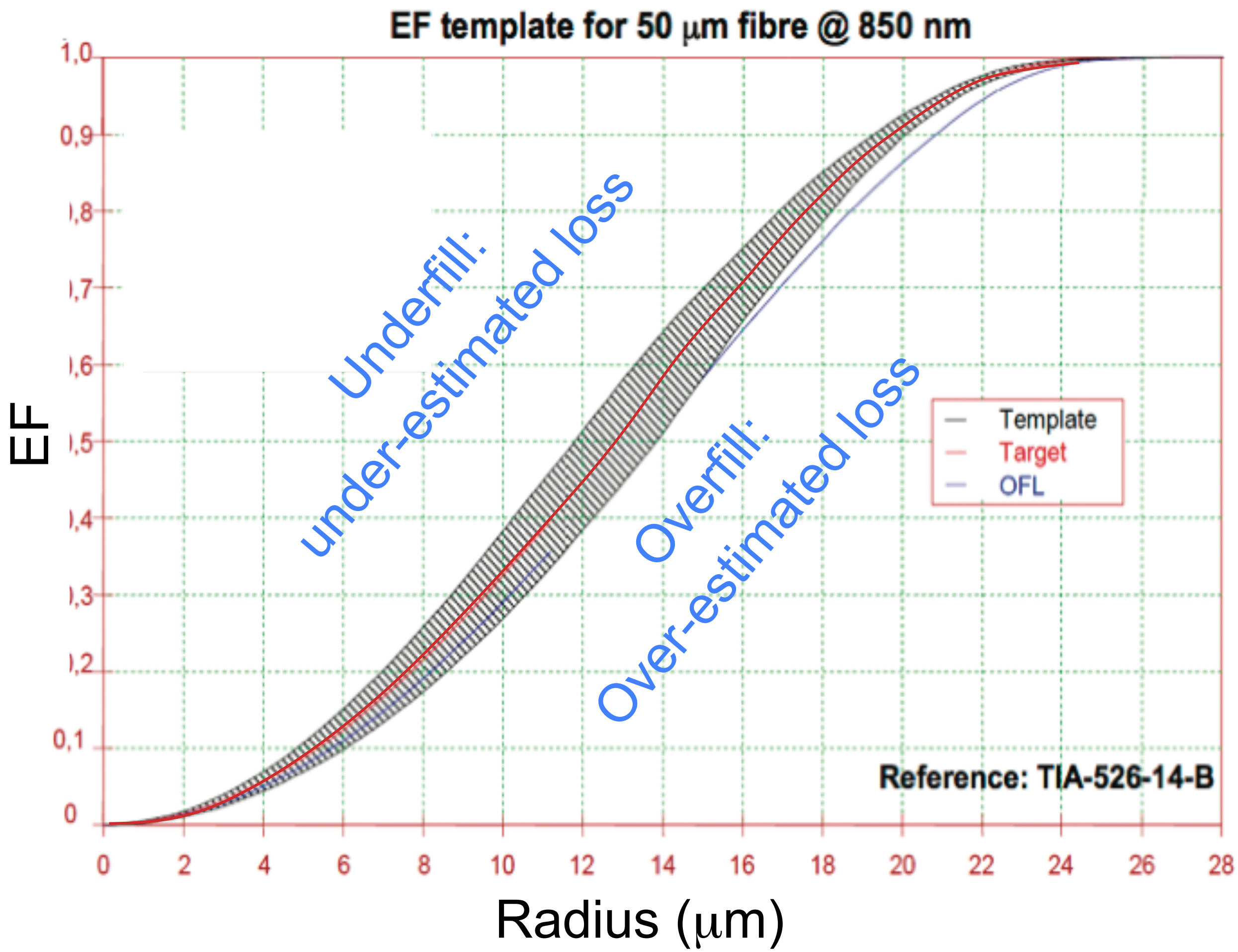
I(r) : mean power averaged on a circle of radius r

$$EF(r) = \frac{\int_0^r I(r')\cdot r'\cdot dr'}{\int_0^{r_{max}} I(r')\cdot r'\cdot dr'}$$



Measuring the modal distribution

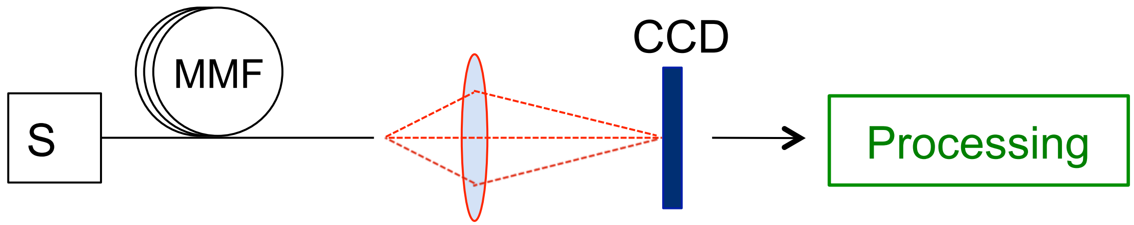
Encircled Flux measured under different illuminating conditions



- EF within template ensures loss measurements comparable within a given tolerance interval

Traceability of EF measurements

Factors influencing EF measurements



- **CCD properties**
  - Linearity
  - Uniformity of CCD camera
  - Dark current
  - Noise
- **Imaging system**
  - Magnification, apparent pixel size
  - Image focussing
  - Stray light
- **Data processing**
  - Fibre positioning (centroid of intensity distribution)
  - Numerical integration
  - Speckle averaging

Traceability of EF measurements

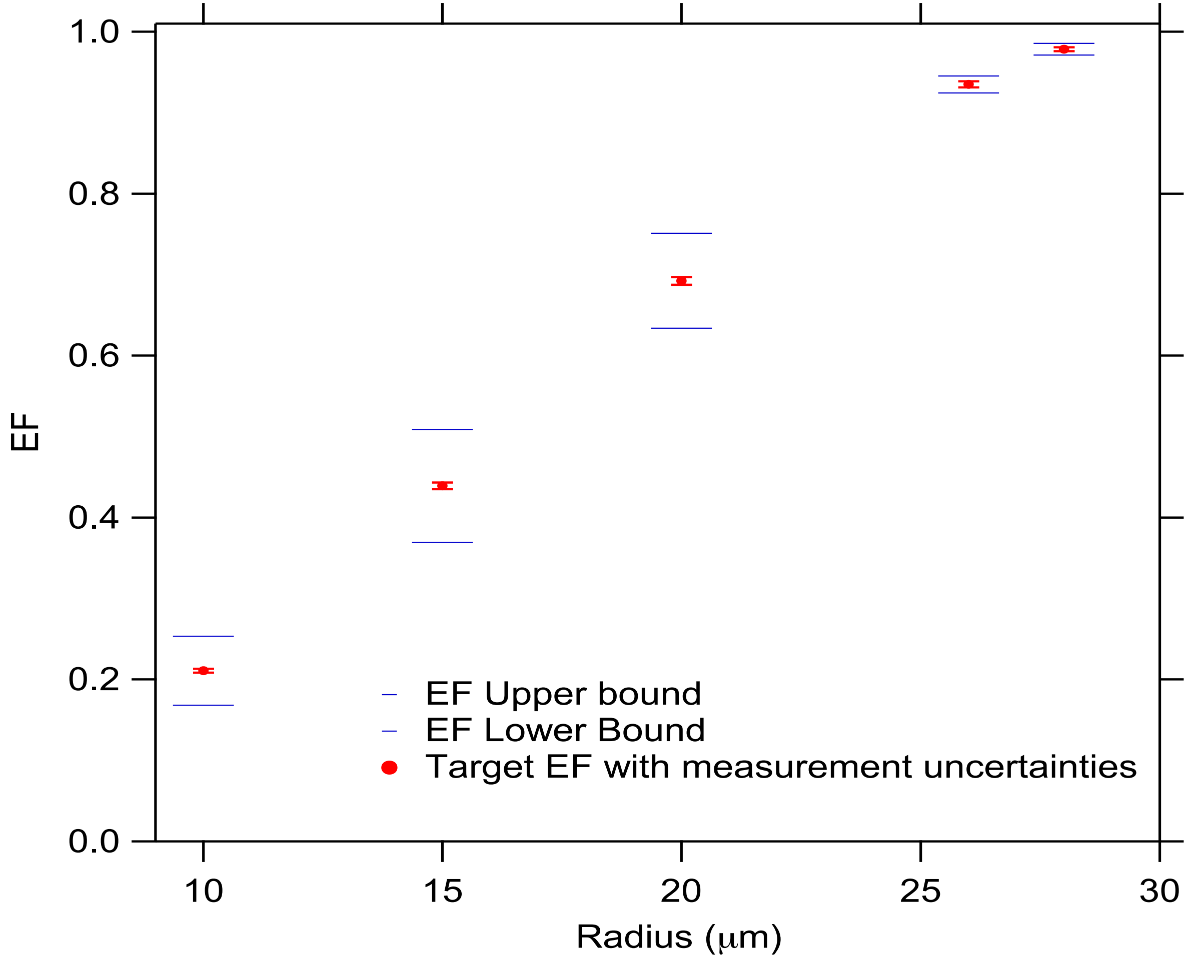
Uncertainty budget

- Expanded combined standard uncertainty

	Radius (µm)				
	10	**15**	**20**	**26**	**28**
$u_{CCD\ Linearity}$ (%)	0.29	0.22	0.14	0.04	0.01
$u_{CCD\ Uniformity}$ (%)	0.28	0.20	0.13	0.08	0.06
u_A (%)	0.10	0.09	0.08	0.07	0.05
$u_{Length\ calibration}$ (%)	0.38	0.35	0.27	0.16	0.09
U_{EF} % (k=2)	**1.12**	**0.93**	**0.68**	**0.39**	**0.24**

Traceability of EF measurements

Comparison of measurements uncertainties with EF limits



- Uncertainties are well within the EF template as defined in IEC 61280-4-1

Limitation of the EF metrics

- The EF model makes a series of important assumptions:
  - Higher order modes contribute to populate essentially the outer region of the fibre core and not the centre.

    This is true with Graded Index (GI) but not with Step Index (SI) fibres.
  - The near field intensity profile is of radial symmetry.

    This not always the case in large core SI and in POF fibres.

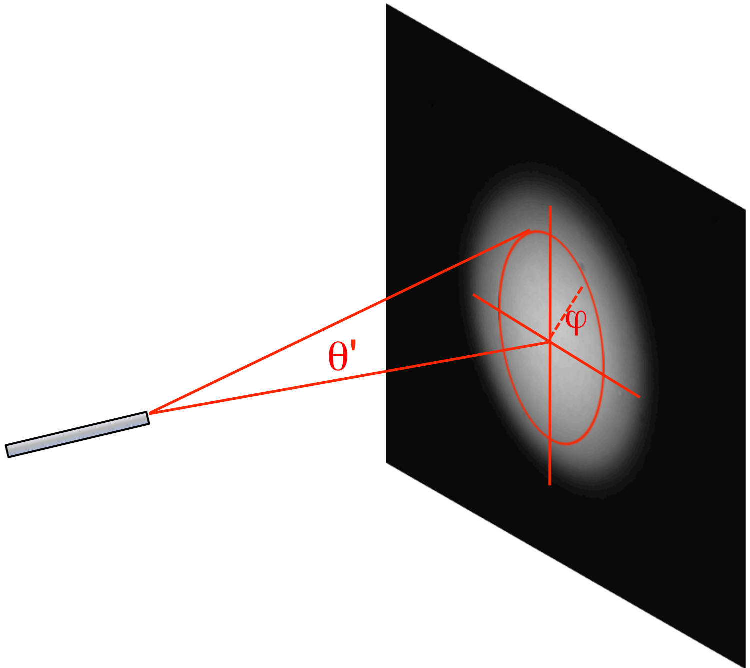
- Necessary to generalize the EF model: $I(r) \rightarrow I(r,\varphi)$

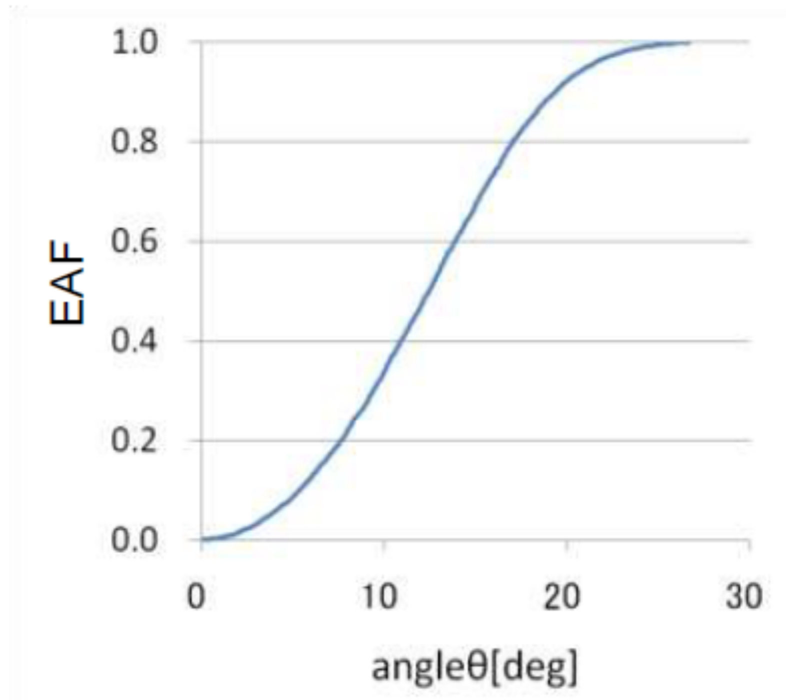
$$EF(r) = \frac{\int_0^{2\pi}\int_0^{r} I(r',\varphi')\cdot r\cdot dr'\cdot d\varphi'}{\int_0^{2\pi}\int_0^{r_{max}} I(r',\varphi')\cdot r\cdot dr'\cdot d\varphi'}$$

Based on that generalized representation, a new metrics is under development

➔ Encircled Angular Flux (EAF)

Encircled Angular Flux (EAF)





$$EAF(\theta') = \frac{\int_0^{2\pi}\int_0^{\theta'} I(\theta,\varphi)\cdot\frac{\sin(\theta)}{\cos^3(\theta)}\cdot d\theta\cdot d\varphi}{\int_0^{2\pi}\int_0^{\theta_{max}} I(\theta,\varphi)\cdot\frac{\sin(\theta)}{\cos^3(\theta)}\cdot d\theta\cdot d\varphi}$$

[2]: M. Kagami, A, Kawasaski, M. Yonemura, et al. , Encircled Angular Flux representation of the modal power distribution and its behaviour in a step index multimode fiber, J. of Lightwave Technol., **34**, 943-951, February 2016.

Normative Aspects

- The need of the industry for comparable loss measurements in multimode fibre components and systems has driven the development of a series of standards for EF measurements:

  - IEC 61280-1-4 Ed. 2 Fibre optic communication subsystem test procedures - Part 1-4: General communication subsystems - Light source encircled flux measurement method

  - TIA/EIA-455-203 - Launched Power Distribution Measurement Procedure for Graded- Index Multimode Fiber Transmitters

  - IEC 61280-4-1/Ed3: Fibre-optic communication subsystem test procedures – Part 4-1: Installed cable plant – Multimode attenuation measurement
    This document defines EF templates (limit values) allowing to guarantee comparable loss measurements within +/- 10 %.

- Calibration standards for fibre optics instruments like powermeters and OTDRs will take benefit form these developments an will include EF requirements in their calibration procedures.

Conclusions

- The performances and the metrological evaluation of multimode fibre components and systems requires a very tight control of the modal distribution

- The Encircled Flux (EF) is one possible way of measuring this modal distribution in a simple way in systems using graded index multimode fibres

- The modal distribution in large core step index and in plastic optical fibres cannot be reliably quantified using the EF metrics. An extension of the model is necessary. The EAF is a very promising metrics, which is currently under development.

➡ Metrology of EAF is investigated in the frame of the EMPIR 14IND13 PhotInd European Research project with following objectives:

- Establish a full traceability for the EAF
- Verify the consistency of the approach through inter-comparisons
- Contribute to the normalization effort in this field
- Promote the development of traceable commercial measuring instruments.

Thank you very much for your attention