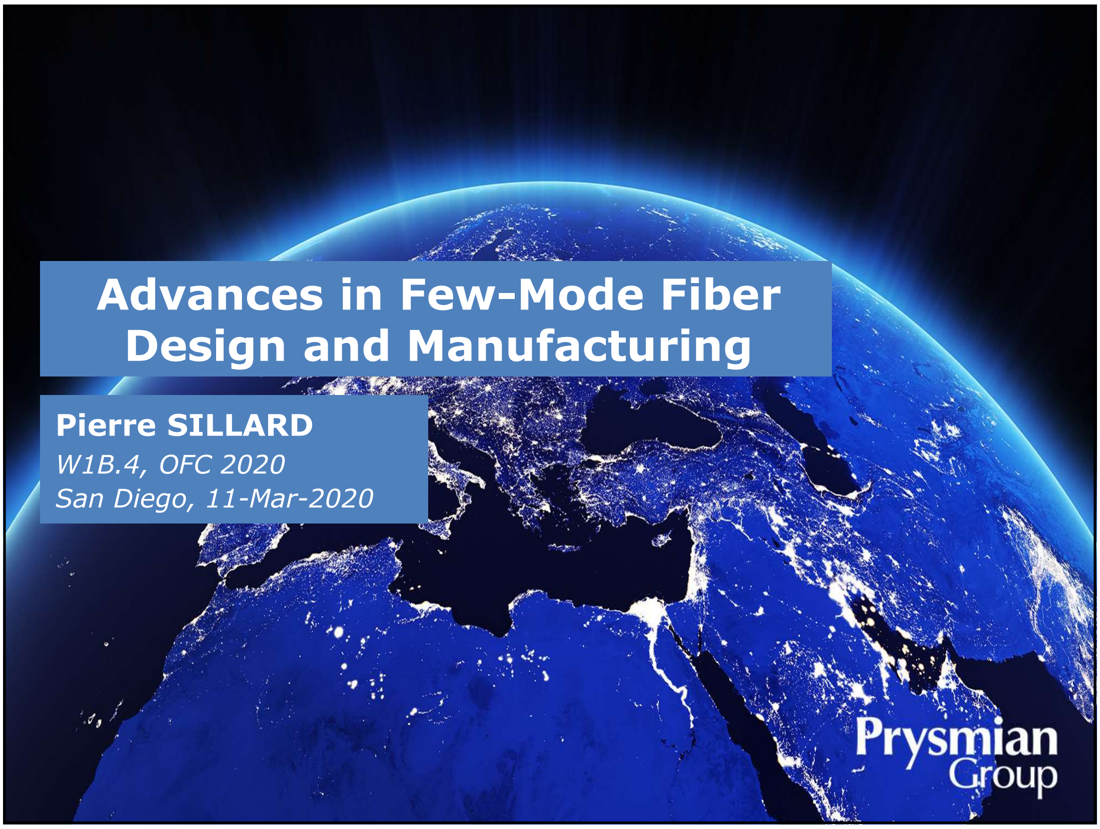

ABSTRACT

This tutorial will show how recent advances in design and manufacturing have improved the performance of few-mode fibers, and what are the challenges to turn them into implementable solutions.

OCIS codes: (060.2280) Fiber design and fabrication; (060.2330) Fiber optics communications

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#No more in this Company/University

OUTLINE

OUTLINE

FMFs and MODE DIVISION MULTIPLEXING (MDM)

FMF in 1977-79* (2-LP-mode fibers for higher bandwidths, ***not for MDM***)

MDM demonstration over MMF in 1982** (2 modes over 10m)

MIMO-MDM demonstrations over MMFs in the 2000s***

MDM transmissions over specifically-designed FMFs in 2011*

9 years of intensive research

- ***New FMFs*, components and subsystems**
- **Impressive record transmissions** (3 modes over 1000s of km, 6 modes over 100s of km, 45 modes and 100s of Tbps over 10s of km)
- **Significant efforts to turn research demonstrations into implementable solutions** (10s and 100s of Gbps without MIMO, real-time 2x2 & 4x4 MIMOs and *6x6 MIMO* [*coupled-core fiber*])

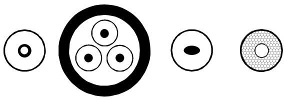
**J. Sakai and T. Kimura, Opt. Lett. 1, p.169 (1977); K. Kitayama et al., IEEE-JQE 15, p.6; L.G. Cohen et al., OFC, ThC2 (1979)*
***S. Berdagué and P. Facq, Appl. Opt. 21, p.1950 (1982)*
****H.R. Stuart, OFC'00, ThV2; C.P. Tsekrekos et al., ECOC'05, We4.P.113; S. Schöllmann OFC'07, OTuL2; B.C. Thomsen, OFC'10, OThM6; B. Franz et al., ECOC'10, Tu.3.C.4*
**OFC'11: A. Li at al., PDPB8; M. Salsi et al., PDPB9; R. Ryf et al., PDPB10*

FMFs

STANDARD FIBERS

Standard manufacturing processes, standard 125 & 250µm dimensions (large scale production), **low attenuations, easy splicing**

NON-STANDARD FIBERS



Mostly non-standard manufacturing processes and non-standard dimensions (short lengths), **relatively high attenuations** (≥0.25 or ≥0.5dB/km)

- **OAM** Fibers
- **RING** Fibers
- **MULTI-ELEMENT** Fibers
- **ELLIPTICAL-CORE** Fibers
- **HOLLOW-CORE PHOTONIC-BANDGAP** Fibers

FMFs

STANDARD FIBERS

Standard manufacturing processes, standard 125 & 250µm dimensions (large scale production), **low attenuations, easy splicing**

Weak Coupling: **Cross-Talk** (**XT**) **is minimized**, so that each (group of) mode(s) can be separately detected at reception

➔ ***No MIMO****: Mode Group Division Multiplexing with Direct Detection*
- ➪ ***4 LP Mode Groups*** *(>200Gbps, bidirectional,* ***20km****)**
- ➪ ***6 LP Mode Groups*** *(60Gbps,* ***10km****)***

➔ *Simple* ***2×2*** *and* ***4×4 MIMOs*** *with Coherent Detection*
- ➪ ***402.7 Tbps*** *(6 LP modes [****10 spatial modes****], 48km)****
- ➪ ***Real-Time*** *(1.05Tbps, 6 LP modes [****10 spatial modes****], 48km)*****

Full MIMO: **DMGD minimized** so that all modes are simultaneously detected at reception and that **MIMO** can compensate for **XT**

➔ ***2N×2N MIMO*** *(N spatial modes) with Coherent Detection*
- ➪ ***45 spatial modes*** *(101Tbps, 26.5km,* ***90×90*** *MIMO)**
- ➪ ***266 Tbps*** *(90km,* ***12×12*** *MIMO)***
- ➪ ***6,300 km*** *(1Tbps, 6×6 MIMO)***;* ***3,060km*** *(40.2Tbps,* ***6×6*** *MIMO)*****

**K. Benyahya et al., ECOC'18, Tu1G.5*
***D. Ge et al., OFC'18, W4K.3*
****D. Soma et al., ECOC'19, W.2.A.2*
*****Igarashi et al., ECOC'19, W.2.A.3*

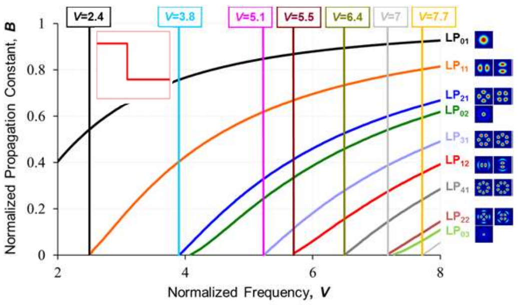
**R. Ryf et al., ECOC'18, Th3B.1*
*** Y. Wakayama et al., OFC'18, W4C.1*
****K. Shibahara et al., OFC'18, Th4C.6*
*****K. Shibahara et al., OFC'19, W3F.2*

OUTLINE

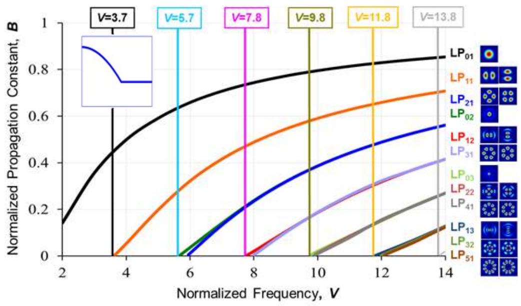
BASICS*

Normalized **frequency**: $V = \frac{2\pi}{\lambda} \cdot a \cdot \sqrt{n_{co}^2 - n_{cl}^2}$ [a: *Core radius*, n_{co}: *Core index*]

Normalized **propagation constant**: $B = \frac{n_{eff}^2 - n_{cl}^2}{n_{co}^2 - n_{cl}^2}$ [n_{eff}: *effective index of the mode*]



Step-index Profiles for which **Δn_{eff} is maximized** (>**0.5×10^{-3}**) to limit **XT**, while maintaining Attenuation <**0.25**dB/km and A_{eff} >**80**µm²



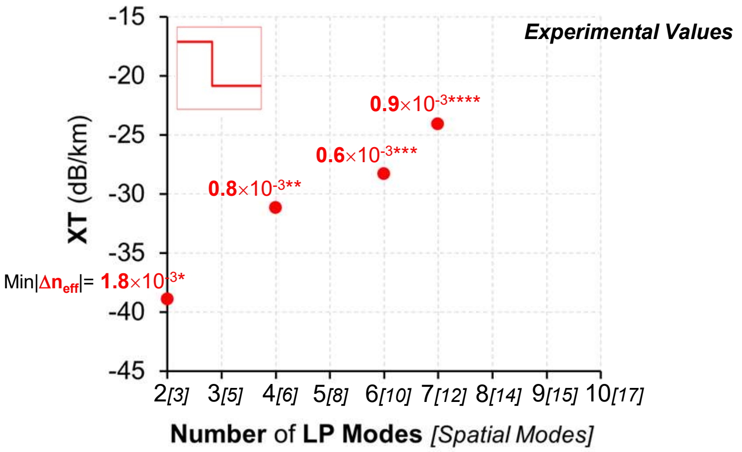
Graded-index Profiles for which **DMGDs is minimized** (<**100s** of ps/km) to limit **MIMO** complexity, while maintaining Attenuation <**0.25**dB/km and A_{eff} >**80**µm²

➔ ***Highest possible V**, allowing for the **1st modes** to propagate while cutting off the undesired higher-order modes, in order to ensure **the highest possible B** (**low Bend Losses** <**10**dB/turn at 10mm bend radius)*

P. Sillard et al., JLT **32, p.2824 (2014); OFC'16, Th1J.1*

OUTLINE

WEAKLY-COUPLED FMFs: XT *[worst value between 2 LP modes]*



XT is high because modes spatially overlap

XT increases with the # of modes

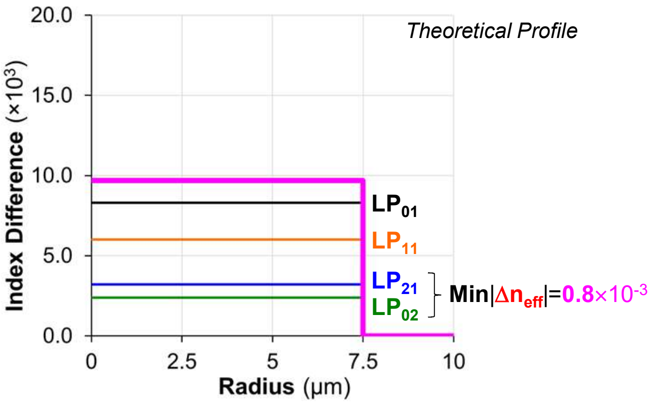
XT >**-35**dB/km for **Min|Δn_{eff}|**<**1.0**×10^{-3} and **# of LP modes ≥4**

➔ ***Only 10s of km w/o full MIMO. What can be done?***

R. Maruyama et al., JLT **35, p.650 (2017)*
***L. Ma et al., ACP'16, AS4A.5*
****D. Soma et al., ECOC'17, M.2.E.3*
*****M. Bigot et al., APC'17, NeM3B.4*

WEAKLY-COUPLED FMFs: *Step-index Profiles*

Increase Δn_{eff} to decrease XT: 4 LP Modes

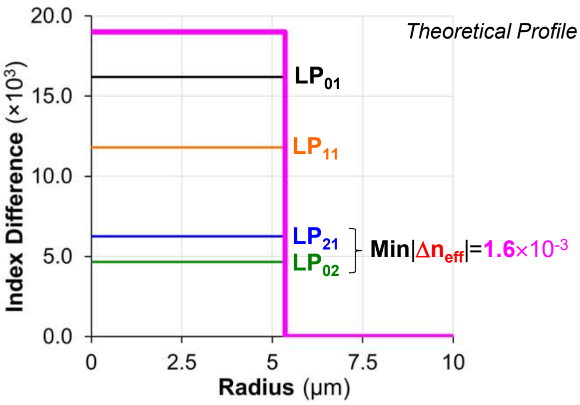


Step-index Profile

- ➪ ***Min|Δn$_{eff}$|*** =**0.8**×10^{-3}
- ➪ ***Attenuation (LP$_{01}$)*** =**0.22**dB/km
- ➪ ***Min|A$_{eff}$|(LP$_{11}$)*** =**118**µm²

WEAKLY-COUPLED FMFs: *Step-index Profiles*

Increase Δn_{eff} to decrease XT: 4 LP Modes

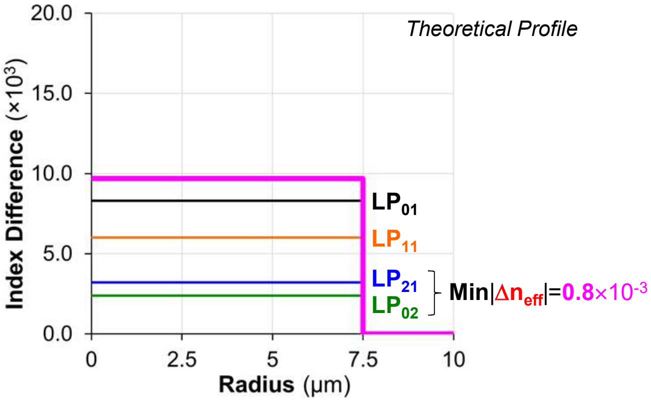


Step-index Profile: *Decrease radius and increase index*

- ➪ ***Min|Δn$_{eff}$|***: *increase from* **0.8** *to* **1.6**×10^{-3}
- ➪ ***Attenuation (LP$_{01}$)***: *increase from* ~**0.22** *to* **0.25-0.30**dB/km
- ➪ ***Min|A$_{eff}$|(LP$_{11}$)***: *decrease from* **118** *to* <**60**µm²

WEAKLY-COUPLED FMFs: *Step-index Profiles*

Increase Δn_{eff} to decrease XT: 4 LP Modes

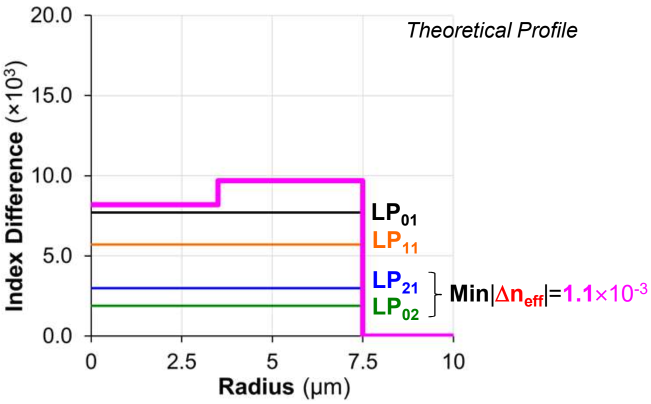


Step-index Profile

- ➪ ***Min|Δn_{eff}|*=0.8×10^{-3}**
- ➪ ***Attenuation (LP_{01})*** ~**0.22**dB/km
- ➪ ***Min|A_{eff}|(LP_{11})*** =**118**μm²

WEAKLY-COUPLED FMFs: *New Index Profiles*

Increase Δn_{eff} to decrease XT: 4 LP Modes



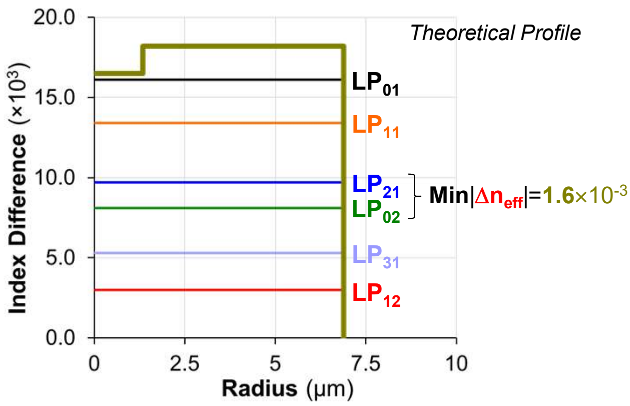
Step-index Profile: *with Depressed-Inner Region**

- ➪ ***Min|Δn_{eff}|****: increase from* **0.8** *to* **1.1**×10^{-3}
- ➪ ***Attenuation (LP_{01})*** ≤**0.22**dB/km
- ➪ ***Min|A_{eff}|*** >**120**μm²

*A.R. May & M.N. Zervas, ECOC'15, P1.131

WEAKLY-COUPLED FMFs: *New Index Profiles*

Increase Δn_{eff} to decrease XT: 6 LP Modes



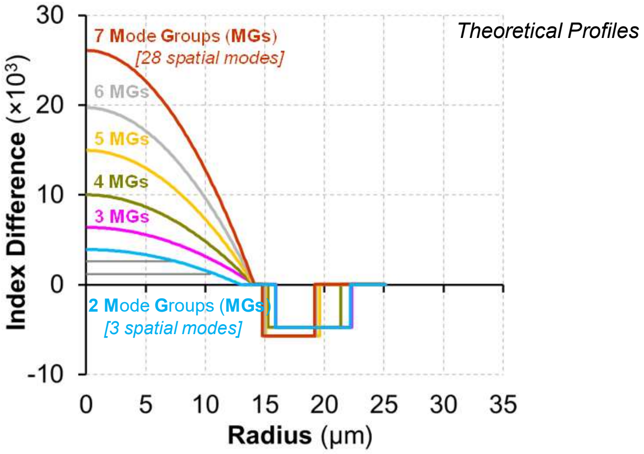
Step-index Profile: ***with Depressed-Inner Region****

- ***Min***|Δn_{eff}|: *increase from* **1.0** *to* **1.6**×10⁻³
- ***Attenuation (LP$_{01}$)*** ≤**0.25**dB/km
- ***Min***|***A$_{eff}$***| >**80**µm²

**M. Bigot et al., APC'17, NeM3B.4*

OUTLINE

LOW-DMGD FMFs: *Trench-Assisted Graded-index Profiles*



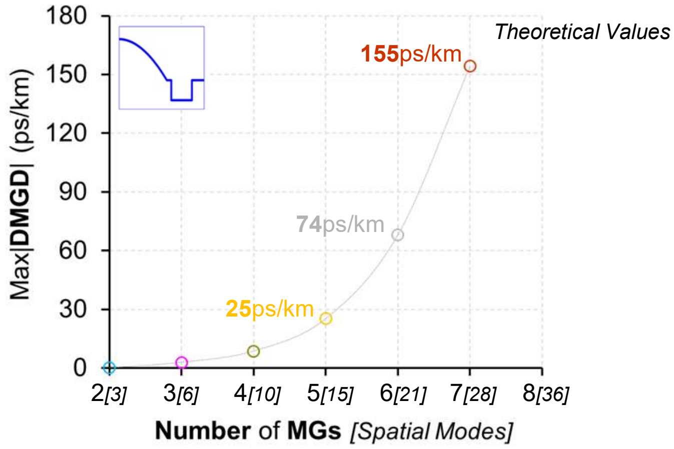
Graded-index Core to minimize DMGDs (as for MMFs)

Trench to reduce bending sensitivity*

- ➔ ***Higher Core indexes*** required to support more modes
- ➔ ***Small Core radii*** to contain Bend Losses and Leaky Modes

*W.A. Reed et al., AT&T TJ 65, p.105 (1987)

LOW-DMGD FMFs: *DMGD*



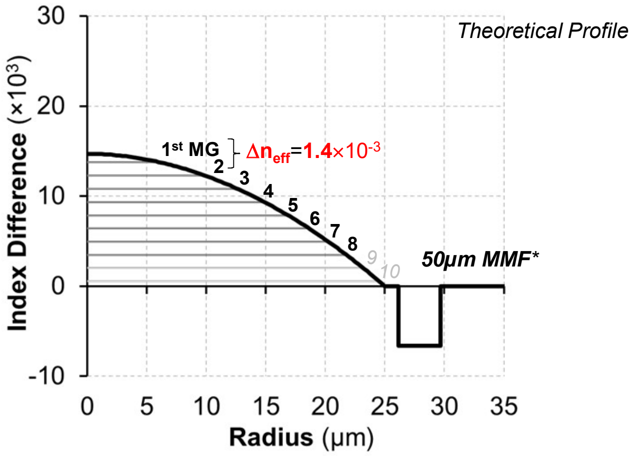
DMGDs increase due to the higher Core indexes*: **critical levels are reached**

➔ ***What can be done?***

- ➪ ***50µm MMF at 1550nm***

*D. Gloge and E.A.J. Marcatili, BSTJ 52, p.1563 (1973)

LOW-DMGD FMFs: *50µm MMF*



$\Delta n_{eff} > 1.4\times10^{-3}$: **weak coupling** between **last MG used** and **1st MG not used**

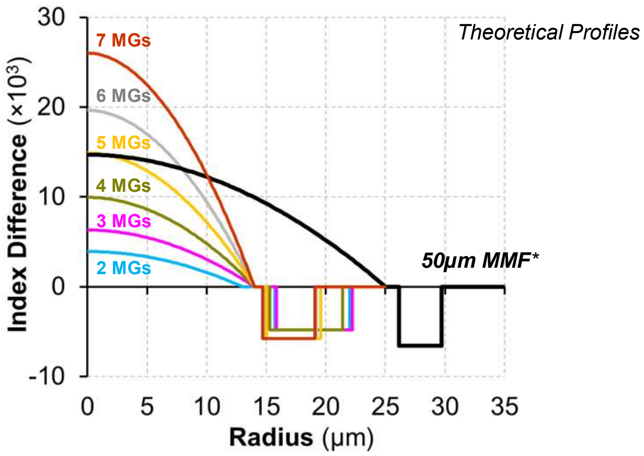
Up to **10 MGs** *[55 spatial modes]* **can selectively be used for MDM**
[9th and 10th MGs being more bend sensitive, might not be suitable for MDM]

DMGDs minimized at **1550nm**

➔ ***Alpha*** parameter of the Graded-index core ***precisely tuned***
➔ ***Trench*** dimensions and position ***carefully adjusted***

P. Sillard et al., JLT **34, p.1672 (2016)*

LOW-DMGD FMFs: *50µm MMF*

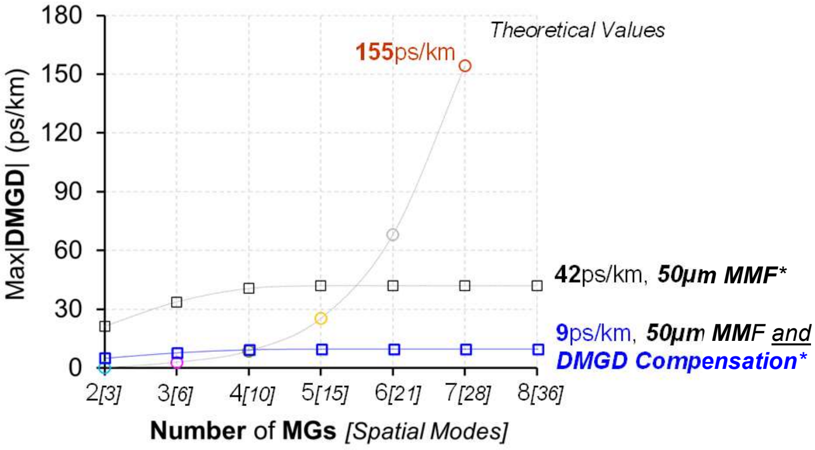


Core index of ***50µm MMF*** ≤ **Core index** of **FMFs** with **MGs** ≥**5**
Core radius of ***50µm MMF*** ≥ **Core radius** of **FMFs**

➔ ***Smaller DMGDs*** *when the* ***# of MGs used*** *>**5***

P. Sillard et al., JLT **34, p.1672 (2016)*

LOW-DMGD FMFs: *50µm MMF*



DMGDs increase due to the higher Core indexes: **critical levels are reached**

➔ ***What can be done?***

⇨ ***50µm MMF at 1550nm and DMGD Compensation****

*P. Sillard et al., JLT **34**, p.1672 (2016)
Matsumoto and K. Nakagawa, Appl. Opt. 18, p.1449 (1979); K. Morishita et al., IEEE Trans. on MTT 30, p.694 (1982)*
P. Sillard et al., OFC'17, Tu2J.4

OUTLINE

1. INTRODUCTION

2. DESIGN
   - 2.1. Basics
   - 2.2. Weakly-Coupled FMFs
   - 2.3. Low-DMGD FMFs

3. MANUFACTURING
   - 3.1. **State of the Art**: Weakly-Coupled FMFs
   - 3.2. Recent Advances
   - 3.3. Perspectives and Challenges

4. CONCLUSION

WEAKLY-COUPLED FMFs

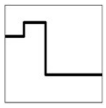
2-LP *[3-Spatial]***-Mode** Fibers [*Not Exhaustive List*]

A. Li *et al.*, OFC'11, PDPB8
A.A. Amin *et al.*, Opt. Ex. **19**, p.16672 (2011)
K. Jespersen *et al.*, OFC'12, OTh3I.4
R. Maruyama *et al.*, OFC'14, M3F.6; OFC'15, M2C.1
T. Mori *et al.*, ECOC'14, Th.1.4.4
C.C. Castineiras Carrero et al., OFC'16, W4F.5

4-LP *[6-Spatial]***-Mode** Fibers

P. Sillard *et al.*, ECOC'11, Tu.5.LeCervin.7
R. Maruyama *et al.*, OFC'15, M2C.1
L. Ma et al.*, *ACP'16*, *AS4A.5

➔ ***Step-index Profiles with Depressed-Inner Region***



6-LP *[10-Spatial]***-Mode** Fibers

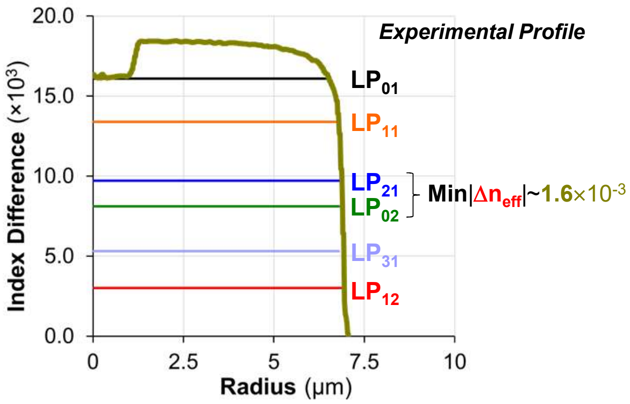
M. Bigot et al.*, *APC'17*, *NeM3B.4
D. Soma *et al.*, ECOC'17, M.2.E.3
L. Shen et al., OFC'18, Th2A.24
D. Ge et al.*, *OFC'18*, *W4K.3

7-LP *[12-Spatial]***-Mode** Fibers

M. Bigot et al.*, *APC'17*, *NeM3B.4

WEAKLY-COUPLED FMFs: *New Index Profiles*

Increase Δn_{eff} to decrease XT: 6 LP Modes



Step-index Profile: ***with Depressed-Inner Region****

➪ ***Min***|Δn_{eff}| ~**1.6**×10⁻³

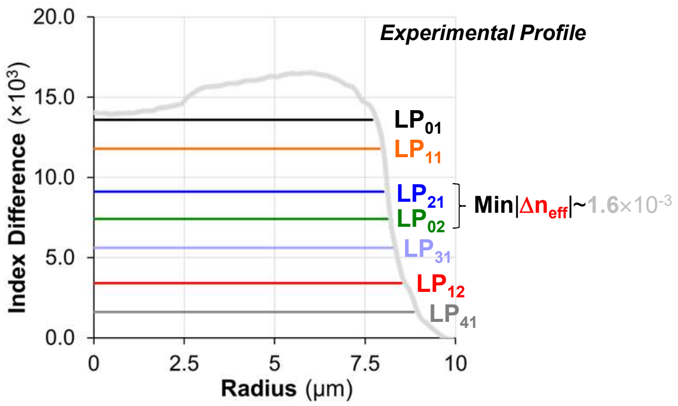
➪ ***Attenuation*** (***LP_{01}***) =**0.25**dB/km

➪ ***Min***|A_{eff}| =**84**µm²

*M. Bigot et al., APC'17, NeM3B.4

WEAKLY-COUPLED FMFs: *New Index Profiles*

Increase Δn_{eff} to decrease XT: 7 LP Modes



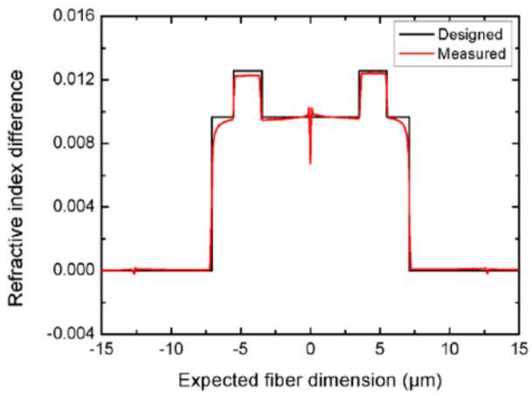
Step-index Profile: ***with Depressed-Inner Region****

- ➪ ***Min***|Δn_{eff}| ~**1.6**×10⁻³
- ➪ ***Attenuation*** (***LP₀₁***) =**0.24**dB/km
- ➪ ***Min***|A_{eff}| =**99**µm²

*M. Bigot et al., APC'17, NeM3B.4

WEAKLY-COUPLED FMFs: *New Index Profiles*

Increase Δn_{eff} to decrease XT: 4 LP Modes



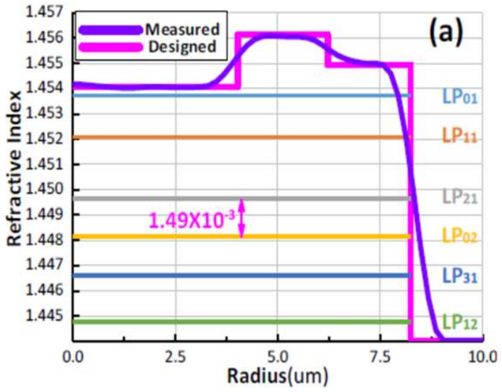
Step-index Profile: ***with Depressed-Inner Region*** (≡***Ring***)*

- ➪ ***Min***|Δn_{eff}| ~**1.8**×10⁻³
- ➪ ***Attenuation*** (***LP₀₁***) =**0.22**dB/km
- ➪ ***Min***|A_{eff}| =**100**µm²

*L. Ma et al., ACP'16, AS4A.5

WEAKLY-COUPLED FMFs: *New Index Profiles*

Increase Δn_{eff} to decrease XT: **6 LP Modes**



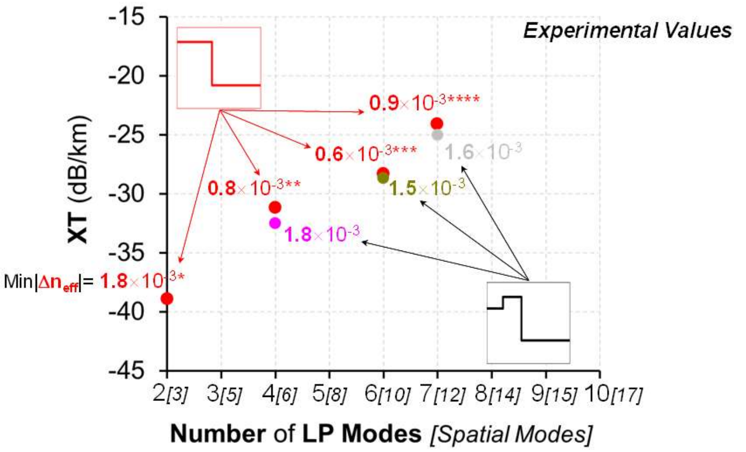
Step-index Profile: ***with Depressed-Inner Region*** *(≡**Ring**)**

- ***Min|Δn_{eff}|*** ~**1.5**×10^{-3}
- ***Attenuation (LP_{01})*** =**0.23**dB/km
- ***Min|A_{eff}|*** =**109**µm²

➔ ***What about XT?***

**D. Ge et al., OFC'18, W4K.3*

WEAKLY-COUPLED FMFs: *XT [worst value between 2 LP modes]*



➔ ***Moderate XT reduction*** ~**2***dB/km*

➔ ***See** 3.3. Perspectives and Challenges*

R. Maruyama et al., JLT **35, p.650 (2017)*
***L. Ma et al., ACP'16, AS4A.5*
****D. Soma et al., ECOC'17, M.2.E.3*
*****M. Bigot et al., APC'17, NeM3B.4*

●L. Ma et al., ACP'16, AS4A.5
●D. Ge et al., OFC'18, W4K.3
●M. Bigot et al., APC'17, NeM3B.4

OUTLINE

LOW-DMGD FMFs

2-MG *[3-Spatial-Mode]* Fibers
R. Ryf *et al.*, OFC'11, PDPB10
T. Sakamoto *et al.*, OFC'12, OM2D.1
L. Grüner-Nielsen *et al.*, OFC'12, PDP5A.1; ECOC'14, P.1.15
M.-J. Li *et al.*, OECC'12, 5C3-2
R. Maruyama *et al.*, ECOC'12, Tu.1.F.2

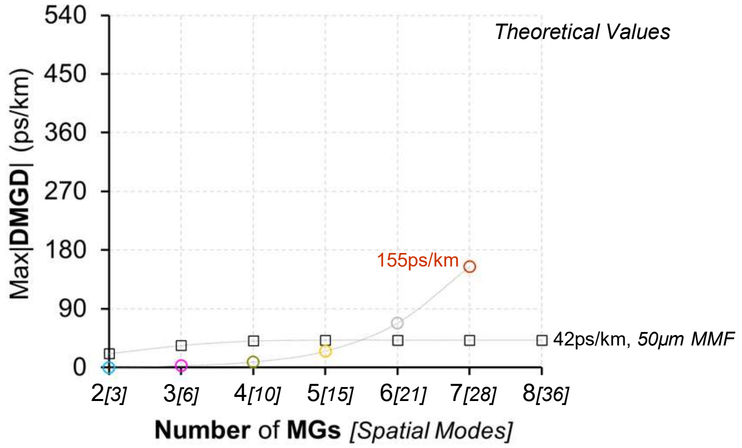
3-MG *[6-Spatial-Mode]* Fibers
T. Mori *et al.*, OFC'13, OTh3K.1
R. Ryf *et al.*, OFC'13, PDPA.1

4-MG *[10-Spatial-Mode]* Fibers
P. Sillard *et al.*, OFC'14, M3F.2
T. Mori *et al.*, OFC'14, M3F.3
P. Sillard et al., JLT 35, p.734 (2017)

5-MG *[15-Spatial-Mode]* Fibers
P. Sillard *et al.*, OFC'15, M2C.2; JLT **34**, p.425 (2016)
N.K. Fontaine *et al.*, OFC'15, Th5C.1

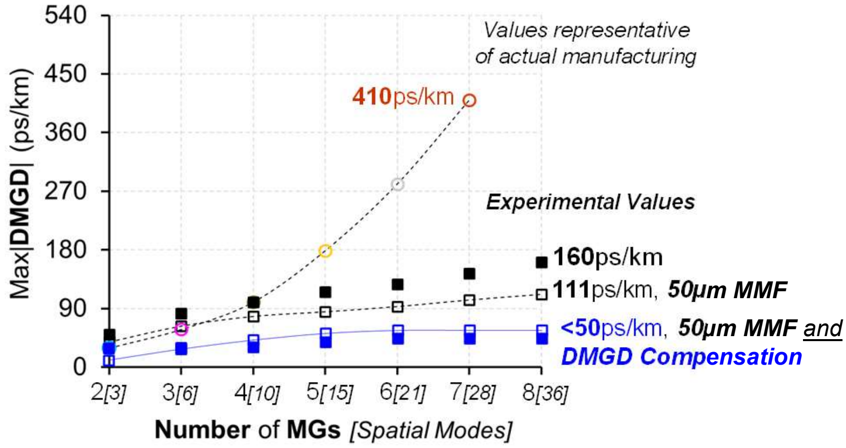
50µm Multi-*[55-Spatial-]****Mode*** Fiber
P. Sillard et al., JLT 34, p.1672 (2016); OFC'17, Tu2J.4
P. Sillard et al., JLT 35, p.1444 (2017)

LOW-DMGD FMFs: *Theoretical Values*



Such low DMGDs cannot be reached given the sensitivity to profile variations (that occur during the manufacturing)

LOW-DMGD FMFs: *Values Representative of Manufacturing*

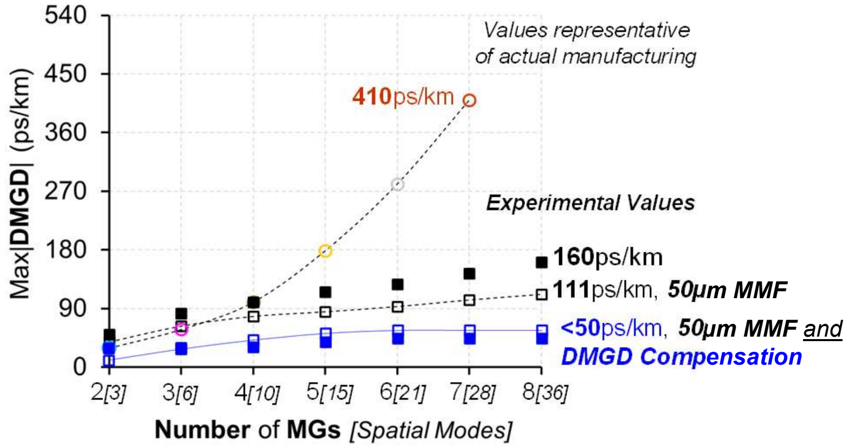


DMGDs calculated from distributions of profiles with σ that match process tolerances: representative of manufacturing

- ⇨ ***Attenuation*** ***(LP_{01})*** =**0.218**dB/km; ***Min***|A_{eff}| =***170***μm^2
- ⇨ ***DMGD Compensation***

■*P. Sillard et al., JLT 34, p.1672 (2016); OFC'17, Tu2J.4*

LOW-DMGD FMFs: *Values Representative of Manufacturing*



DMGDs calculated from distributions of profiles with σ that match process tolerances: representative of manufacturing

➔ ***What can further be done?***

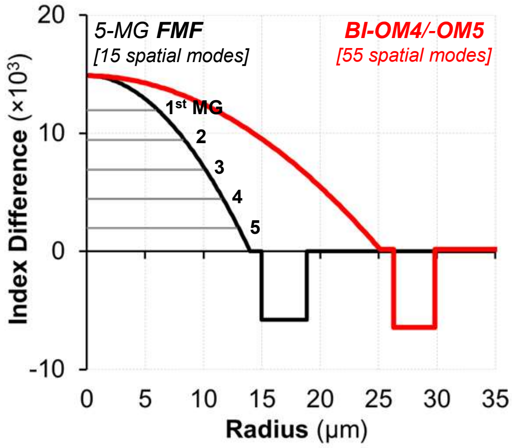
⇨ ***Accurate MM processes for FM manufacturing?***

▪*P. Sillard et al., JLT 34, p.1672 (2016); OFC'17, Tu2J.4*

LOW-DMGD FMFs: *MM Processes*

➔ ***How?***

OM4/OM5 fibers have Core radius of ***25****µm* and guide **10 MGs** *[55 spatial modes]*



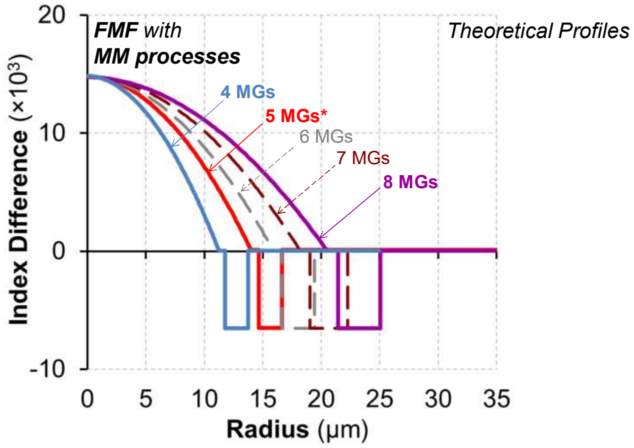
OM4/OM5 preforms can be rescaled to reach **Core radius** of **14**µm **on fiber to guide 5 MGs**, targeting a **diameter** that is 25/14=**1.77×larger***

Alpha has also to be adjusted to minimize **DMGDs** at 1550nm

**P. Sillard et al., OFC'15, M2C.2*

LOW-DMGD FMFs: *MM Processes*

OM4/OM5 fibers have Core radius of ***25****µm* and guide **10 MGs** *[55 spatial modes]*



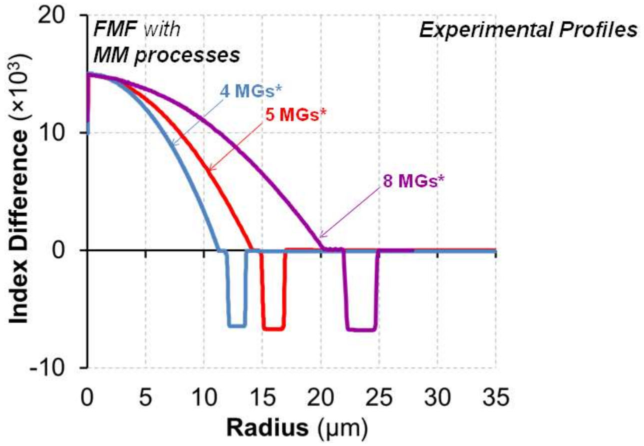
OM4/OM5 preforms can be rescaled to reach **Core radii** from **11.25** to **20.5**µm **on fiber to guide 4 to 8 MGs** *[10 to 36 spatial modes]*

Alphas have to be adjusted to minimize **DMGDs** at 1550nm

**P. Sillard et al., OFC'15, M2C.2*

LOW-DMGD FMFs: *MM Processes*

OM4/OM5 fibers have Core radius of ***25****µm* and guide **10 MGs** *[55 spatial modes]*



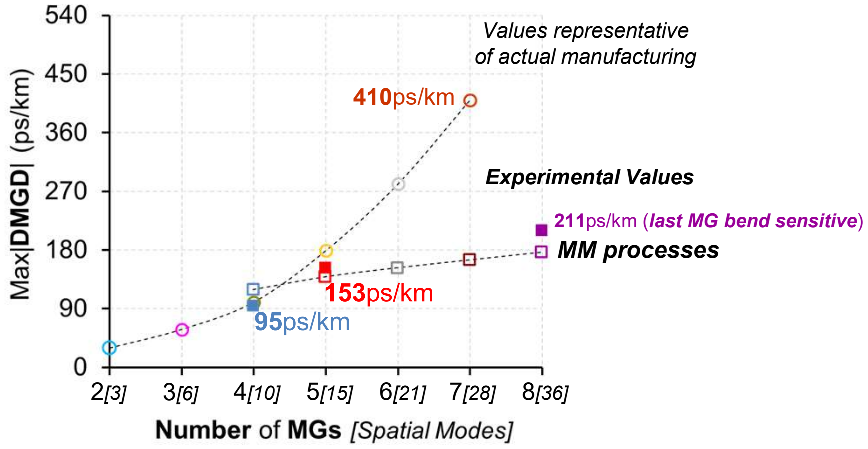
OM4/OM5 preforms can be rescaled to reach **Core radii** from **11.25** to **20.5**µm **on fiber to guide 4 to 8 MGs** *[10 to 36 spatial modes]*

Alphas have to be adjusted to minimize **DMGDs** at 1550nm

**P. Sillard et al., OFC'15, M2C.2*

**P. Sillard et al., JLT 35, p.734 (2017)*
**P. Sillard et al., JLT 35, p.1444 (2017)*

LOW-DMGD FMFs: *MM Processes*



DMGDs calculated from distributions of profiles with σ that match process tolerances: representative of manufacturing

➔ ***What can further be done?***

- ***Accurate MM processes for FM manufacturing** **<u>when # of MGs ≥4</u>***
- ***Attenuation** (LP_{01}) ≤**0.22**dB/km; **Min**|A_{eff}| from **75** to **125**μm²*
- ***DMDG compensation can reduce these values by factors of 2 to 4***

■*P. Sillard et al., OFC'15, M2C.2*
■*P. Sillard et al., JLT 35, p.734 (2017)*
■*P. Sillard et al., JLT 35, p.1444 (2017)*

OUTLINE

WEAKLY-COUPLED FMFs

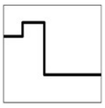
2-LP *[3-Spatial]***-Mode** Fibers [*Not Exhaustive List*]

A. Li *et al.*, OFC'11, PDPB8
A.A. Amin *et al.*, Opt. Ex. **19**, p.16672 (2011)
K. Jespersen *et al.*, OFC'12, OTh3I.4
R. Maruyama *et al.*, OFC'14, M3F.6; OFC'15, M2C.1
T. Mori *et al.*, ECOC'14, Th.1.4.4
C.C. Castineiras Carrero et al., OFC'16, W4F.5

4-LP *[6-Spatial]***-Mode** Fibers

P. Sillard *et al.*, ECOC'11, Tu.5.LeCervin.7
R. Maruyama *et al.*, OFC'15, M2C.1
L. Ma et al., ACP'16, AS4A.5

➔ ***Step-index Profiles with Depressed-Inner Region***



6-LP *[10-Spatial]***-Mode** Fibers

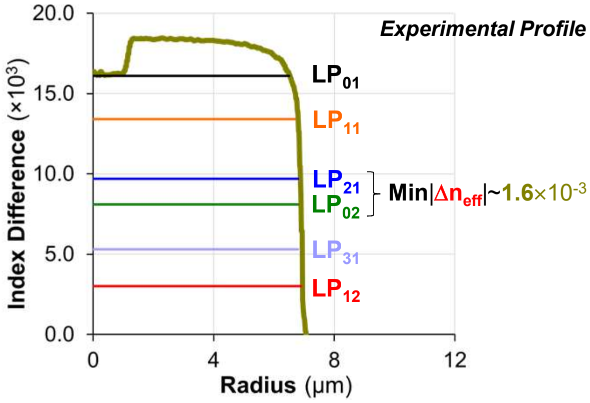
M. Bigot et al., APC'17, NeM3B.4
D. Soma *et al.*, ECOC'17, M.2.E.3
L. Shen et al., OFC'18, Th2A.24
D. Ge et al., OFC'18, W4K.3
M. Bigot et al., OFC'19, M1E.3

7-LP *[12-Spatial]***-Mode** Fibers

M. Bigot et al., APC'17, NeM3B.4

WEAKLY-COUPLED FMFs: *Differential Mode Attenuation (DMA)*

6-LP-Mode Fiber



Step-index Profile with Depressed-Inner Region*

- ***Min***|Δn_{eff}| ~**1.6**×10^{-3}
- ***Attenuation*** (LP_{01}) =**0.25**dB/km **BUT** ***DMA*** =**0.11**dB/km
- ***Min***|A_{eff}| ≥**84**µm²

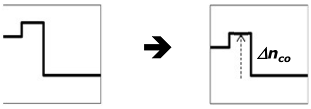
*M. Bigot et al., APC'17, NeM3B.4

WEAKLY-COUPLED FMFs: *DMA*

Main contributors

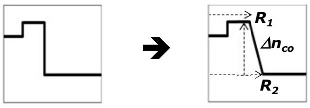
➔ ***R**ayleigh **S**cattering* (***RS***)

- ➪ *Scattering from microscopic inhomogeneities*
- ➪ ***Decreases with order of the mode** because of **smaller confinement in Core***
- ➪ ***Decreases with Core-Cladding index difference**:* Δn_{co}



➔ ***S**mall **A**ngle **L**ight [excess or anomalous] **S**cattering* (***SALS***)*

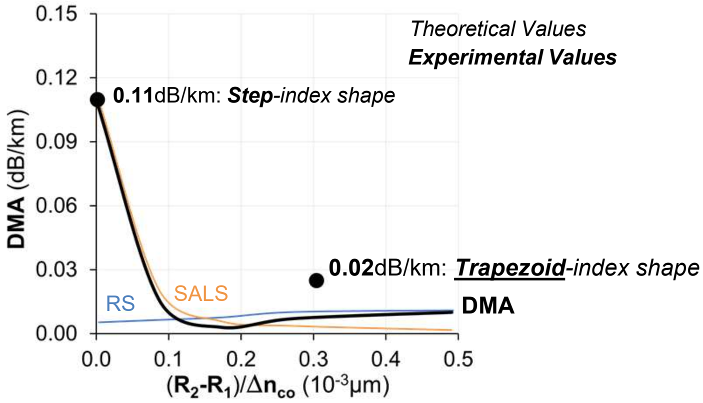
- ➪ *Local scattering points at core-cladding interface*
- ➪ ***Increases with order of the mode** because of **higher amplitude at Core-Cladding interface***
- ➪ ***Decreases with index gradient**, i.e. when* $(R_2\text{-}R_1)/\Delta n_{co}$ ***increases***



*P. Guenot et al., OFC'99, Th2G.1
*M.E. Lines et al., EL **35**, p.1009 (1999)

WEAKLY-COUPLED FMFs: *DMA*

6-LP-Mode Fibers with Depressed-Inner Region*



RS: **Slightly increases** because of **higher** Δn_{core} required to maintain **high** Δn_{eff}

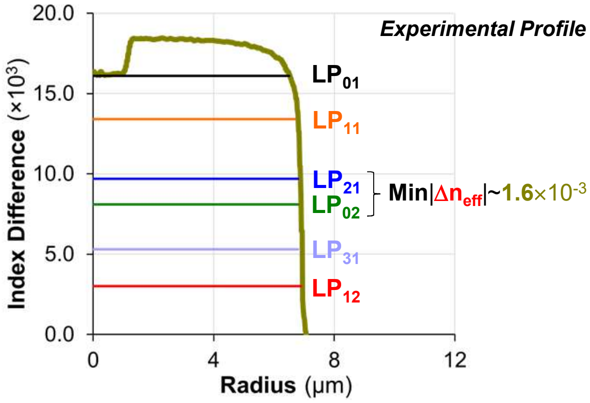
SALS: **Steeply decreases** because of **smaller index gradient**

➔ ***DMA**: **Minimized** <**0.01**dB/km at* $(R_2\text{-}R_1)/\Delta n_{core}$ ~$\mathbf{0.2\times10^{-3}}$*µm*

*M. Bigot et al., OFC'19, M1E.3

WEAKLY-COUPLED FMFs: DMA

6-LP-Mode Fibers with Depressed-Inner Region



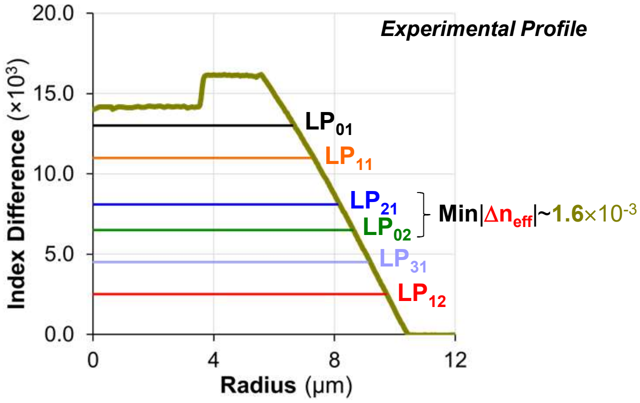
Step-index shape*

- ➪ ***Min***|Δn_{eff}| ~**1.6**×10^{-3}
- ➪ ***Attenuation*** (LP_{01}) =**0.25**dB/km and ***DMA*** =**0.11**dB/km
- ➪ ***Min***|A_{eff}| ≥**84**μm²

*M. Bigot et al., APC'17, NeM3B.4

WEAKLY-COUPLED FMFs: DMA

6-LP-Mode Fibers with Depressed-Inner Region



Trapezoid*-index shape

- ➪ ***Min***|Δn_{eff}| ~**1.6**×10^{-3}
- ➪ ***Attenuation*** (LP_{01}) =**0.24**dB/km and ***DMA*** ≤**0.02**dB/km
- ➪ ***Min***|A_{eff}| ≥**100**μm²

**M. Bigot et al., OFC'19, M1E.3*

OUTLINE

LOW-DMGD FMFs

2-MG *[3-Spatial-Mode]* Fibers
R. Ryf *et al.*, OFC'11, PDPB10
T. Sakamoto *et al.*, OFC'12, OM2D.1
L. Grüner-Nielsen *et al.*, OFC'12, PDP5A.1; ECOC'14, P.1.15
M.-J. Li *et al.*, OECC'12, 5C3-2
R. Maruyama *et al.*, ECOC'12, Tu.1.F.2

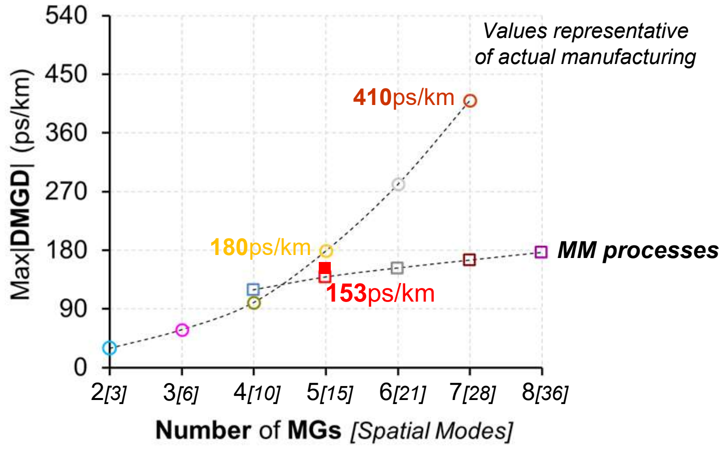
3-MG *[6-Spatial-Mode]* Fibers
T. Mori *et al.*, OFC'13, OTh3K.1
R. Ryf *et al.*, OFC'13, PDPA.1

4-MG *[10-Spatial-Mode]* Fibers
P. Sillard *et al.*, OFC'14, M3F.2
T. Mori *et al.*, OFC'14, M3F.3
P. Sillard et al., JLT ***35****, p.734 (2017)*

5-MG *[15-Spatial-Mode]* Fibers
P. Sillard *et al.*, OFC'15, M2C.2; JLT **34**, p.425 (2016)
N.K. Fontaine *et al.*, OFC'15, Th5C.1
D. Molin et al., OFC'18, W3C.1

50µm Multi-*[55-Spatial-]****Mode*** Fiber
P. Sillard et al., JLT ***34****, p.1672 (2016); OFC'17, Tu2J.4;* ***R. Ryf et al., ECOC'18, Th3B.1***
P. Sillard et al., JLT ***35****, p.1444 (2017)*

LOW-DMGD FMFs: *MM Processes*



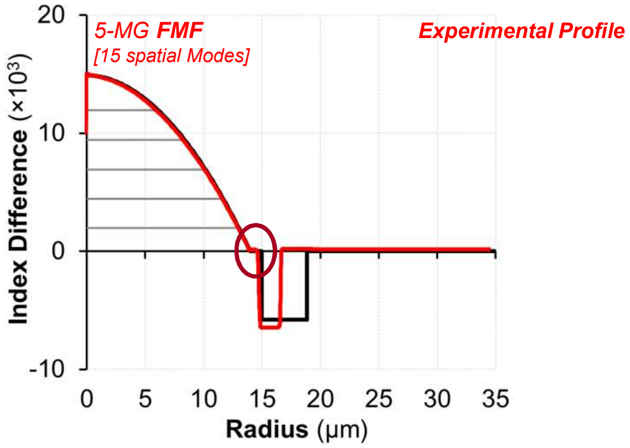
Experimental value of 153ps/km < 180ps/km for standard FMFs

➔ ***How to improve this result?***

■P. Sillard et al., OFC'15, M2C.2

LOW-DMGD FMFs: *MM Processes with Improved Design*

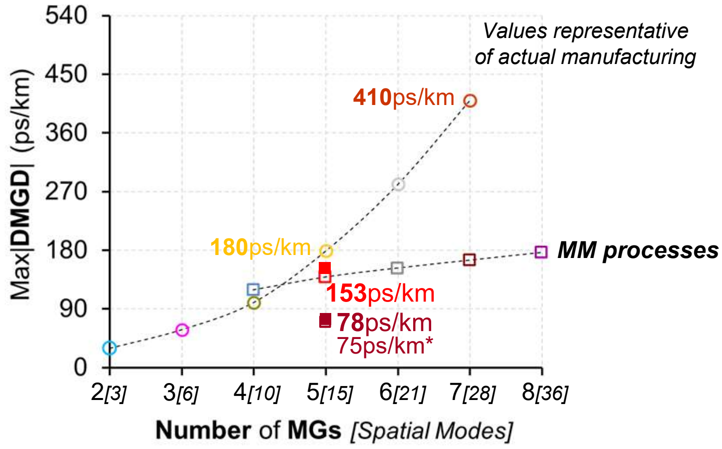
OM4/OM5 preforms rescaled to reach **Core radius** of **14**μm **on fiber to guide 5 MGs**, targeting a **diameter** that is 25/14=**1.77**×**larger**



Trench-Core distance to be adjusted to further reduce **DMGDs***

■P. Sillard et al., OFC'15, M2C.2
P. Sillard et al., JLT **34, p.425 (2016)*

LOW-DMGD FMFs: *MM Processes*

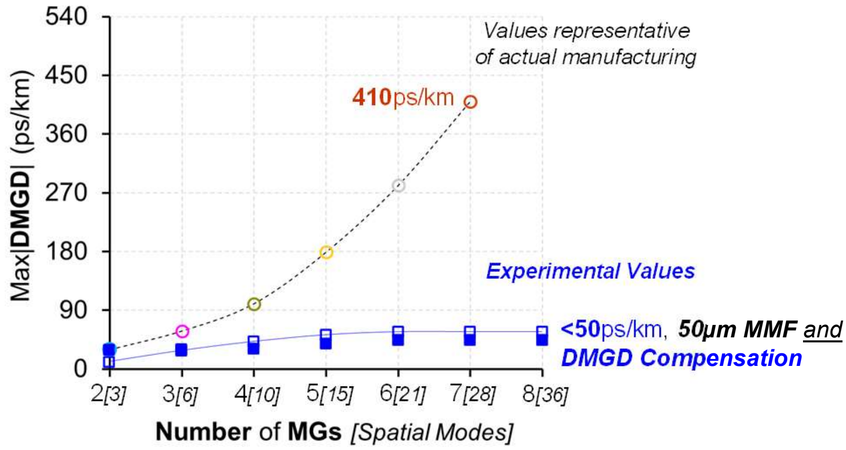


Experimental value of 78ps/km ~calculated value of 75ps/km*

➔ ***Lowest DMGD reported for a 15-Spatial-Mode Fiber***

■*P. Sillard et al., OFC'15, M2C.2*
P. Sillard et al., JLT* ***34**, p.425 (2016)*
■***D. Molin et al., OFC'18, W3C.1***

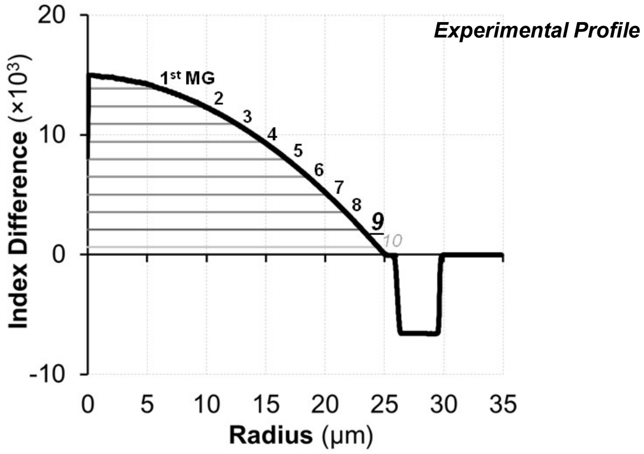
LOW-DMGD FMFs: *50µm MMF and DMGD Compensation*



8 MGs considered: *9th and 10th MGs being more bend sensitive, might not be suitable for MDM*

■***P. Sillard et al., OFC'17, Tu2J.4***

LOW-DMGD FMFs: *50µm MMF and DMGD Compensation*

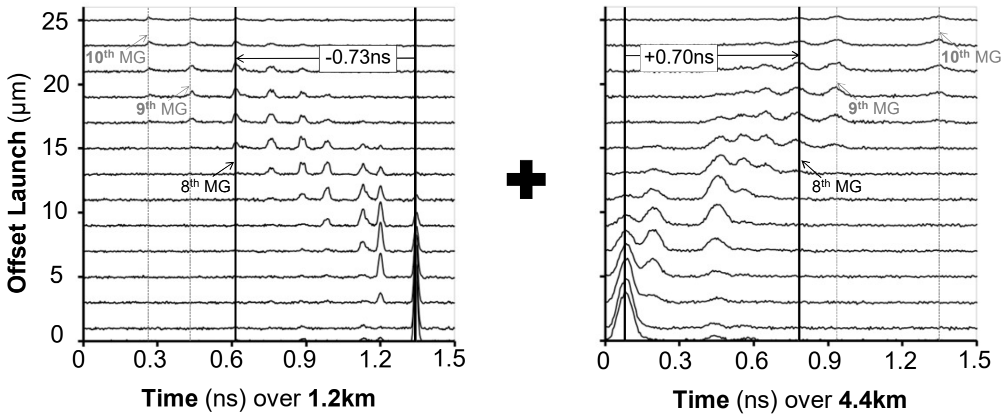


Not 8 but **9 MGs** *[45 spatial modes]* **transmitted over 26.5km** (101Tbps, 202bps/Hz, 90×90 MIMO)*

➔ ***What about the DMGD of the 9th MG?***

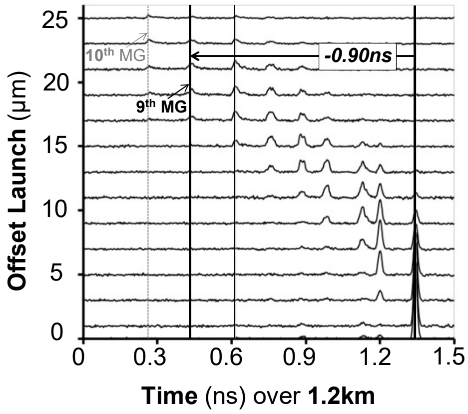
**R. Ryf et al., ECOC'18, Th3B.1*

LOW-DMGD FMFs: *50µm MMF and DMGD Compensation*

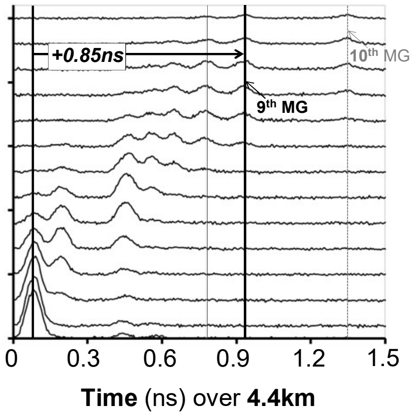


8th MG almost **perfectly compensated**: **5**ps/km ~30*[=-730+700]*ps/5.6km

LOW-DMGD FMFs: *50µm MMF and DMGD Compensation*



✚



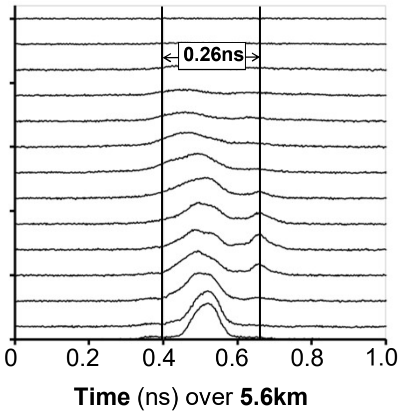
8th MG almost **perfectly compensated**: **5**ps/km ~30*[=-730+700]*ps/5.6km

9th MG almost **perfectly compensated**: **9**ps/km ~30*[=**-900+850**]*ps/5.6km

➔ ***DMGDs* come from the lower-order MGs not perfectly compensated because of process variability**

LOW-DMGD FMFs: *50µm MMF and DMGD Compensation*

=



8th MG almost **perfectly compensated**: **5**ps/km ~30*[=-730+700]*ps/5.6km

9th MG almost **perfectly compensated**: **9**ps/km ~30*[=**-900+850**]*ps/5.6km

➔ ***DMGD*** *~260/5.6 <**50**ps/km (1st **9 MGs**)*

➔ ***10s of km of links** with **DMGDs <50**ps/km (1st **9 MGs**)*

OUTLINE

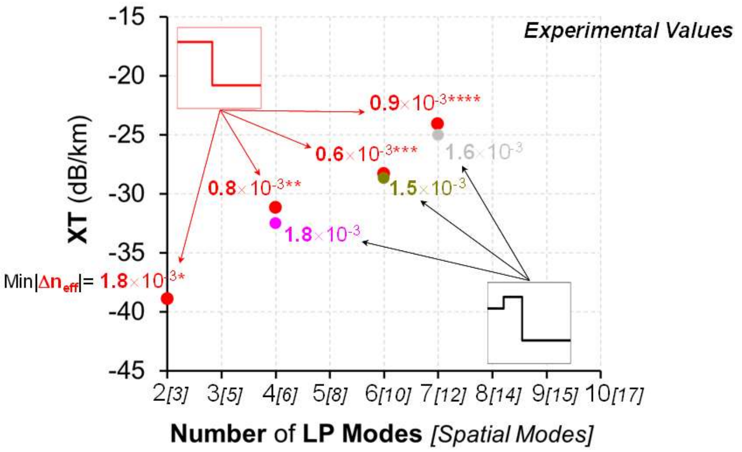
1. INTRODUCTION

2. DESIGN
   2.1. Basics
   2.2. Weakly-Coupled FMFs
   2.3. Low-DMGD FMFs

3. MANUFACTURING
   3.1. State of the Art
   3.2. Recent Advances
   3.3. **Perspectives and Challenges**: Weakly-Coupled FMFs

4. CONCLUSION

WEAKLY-COUPLED FMFs: XT *[worst value between 2 LP modes]*



→ ***Min***|*Δn_{eff}*|*: increase from* **0.6-0.9** *to* **1.5-1.8**$\times 10^{-3}$

→ ***Moderate XT reduction*** *~2dB/km*

→ ***Why?***

R. Maruyama et al., JLT **35, p.650 (2017)*
***L. Ma et al., ACP'16, AS4A.5*
****D. Soma et al., ECOC'17, M.2.E.3*
*****M. Bigot et al., APC'17, NeM3B.4*

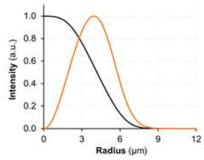
●***L. Ma et al., ACP'16, AS4A.5***
●***D. Ge et al., OFC'18, W4K.3***
●***M. Bigot et al., APC'17, NeM3B.4***

WEAKLY-COUPLED FMFs: *XT*

XT depends not only on Δn_{eff} but also on Mode Overlapping

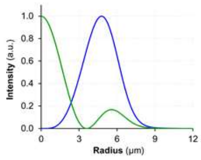
2 LP modes: **Min**$|\Delta n_{eff}|=|n_{eff,01}-n_{eff,11}|$

- ➪ ***Min***$|\Delta n_{eff}|$: *increase from* **1.0** *to* **1.8**$\times 10^{-3}$
- ➪ ***Mode overlapping*** *<45%*
- ➪ ***XT reduction*** *~**10** to **20**dB/km**

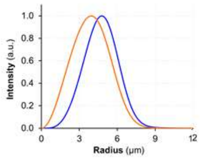


4, 5, 6, 7 LP modes: **Min**$|\Delta n_{eff}|=|n_{eff,21}-n_{eff,02}|$

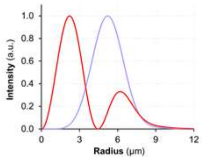
- ➪ ***Min***$|\Delta n_{eff}|$: *increase from* **0.6-0.9** *to* **1.5-1.8** $\times 10^{-3}$
- ➪ ***Mode overlapping*** *<35%*
- ➪ ***XT reduction*** *~**2**dB/km*



- ➪ $|n_{eff,11}-n_{eff,21}|$~**3**$\times 10^{-3}$
- ➪ ***Mode overlapping*** *>75%*



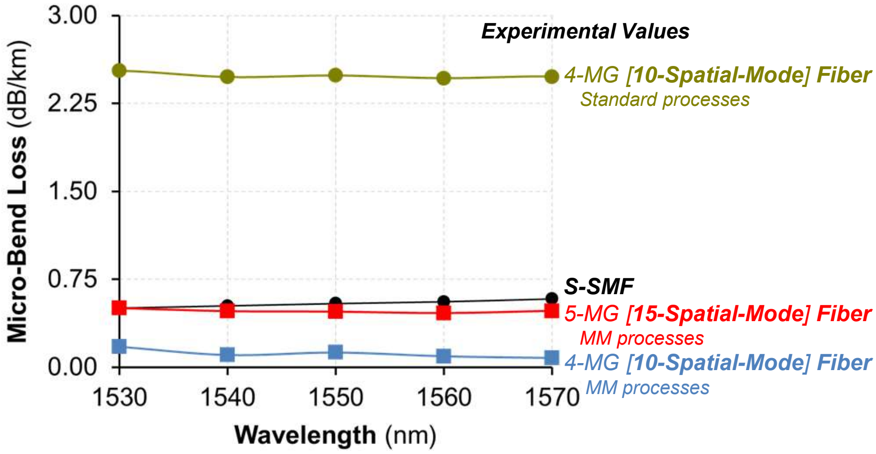
- ➪ $|n_{eff,31}-n_{eff,12}|$~**2.3**$\times 10^{-3}$
- ➪ ***Mode overlapping*** *>60%*



R. Maruyama et al., JLT **35, p.650 (2017)*

OUTLINE

LOW-DMGD FMFs: Cablability

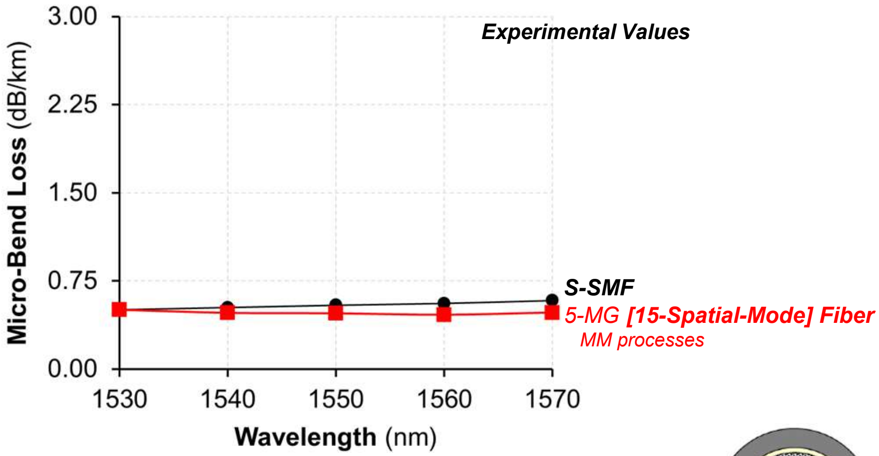


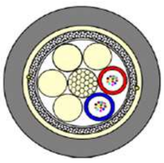
Increasing effective index difference between guided modes and radiation/leaky modes reduces micro-bending sensitivity*

- ⇨ ***Micro-bend losses equivalent to or lower than those of S-SMFs***
- ⇨ *Allows for **practical deployments** in **telecom networks** (small added losses when fibers are put in cables and submitted to harsh environments)*

●*P. Sillard et al., OFC'14, M3F.2*
**R. Olshansky, Appl. Opt. 14, p.935 (1975)*
■*P. Sillard et al., JLT 35, p.734 (2017)*
■*P. Sillard et al., OFC'15, M2C.2; D. Molin et al., OFC'18, W3C.1*

LOW-DMGD FMFs: Cablability and Field Trial



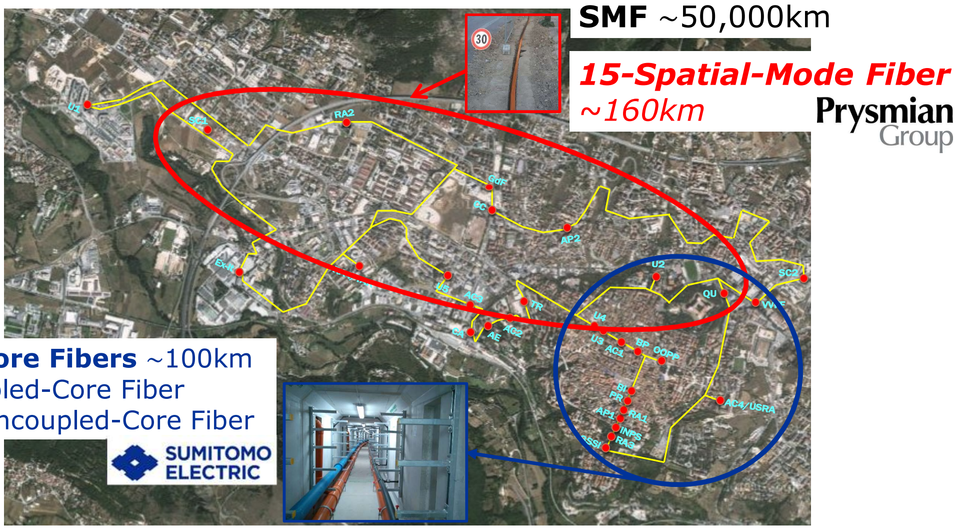


- ⇨ ***20km duct cable** (2 loose tubes with 4 × **15-Spatial-Mode Fiber**) **to be deployed in L'Aquila, Italy***
- ⇨ *Part of **fiber-optic infrastructure around the city center of L'Aquila,** within* INCIPICT*
- ⇨ ***Living lab**, a test-bed available to international research community*

■*P. Sillard et al., OFC'15, M2C.2; D. Molin et al., OFC'18, W3C.1*
**C. Antonelli et al., 2018 IEEE 5GWF, p.410–415 (2018)*

LOW-DMGD FMFs: *Cablability and Field Trial*

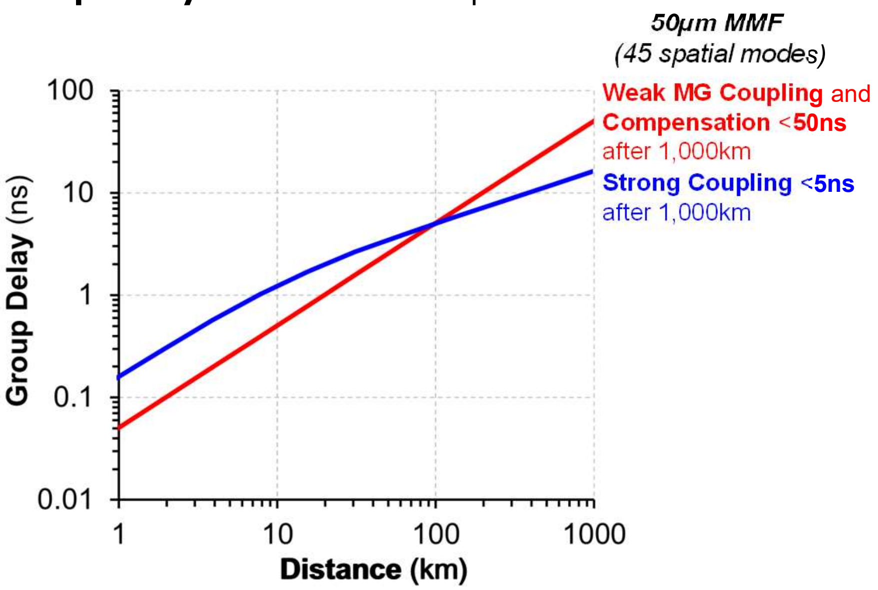
INCIPICT
Innovating City Planning through Information & Communications Technologies



LOW-DMGD FMFs: *Mode Coupling*

Weak: **Group Delay** scales linearly with distance

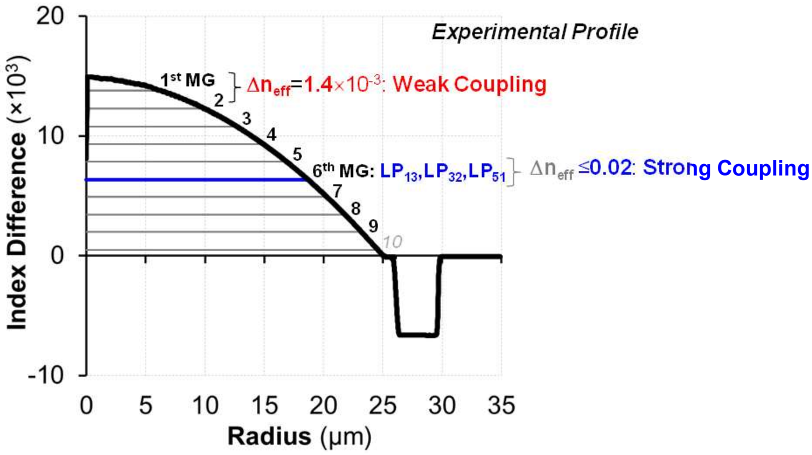
Strong: **Group Delay** scales with the square-root of distance*



*S.D. Personick, BSTJ 50, p.843 (1971)

LOW-DMGD FMFs: *Mode Coupling*

Modes in MGs are Strongly Coupled*



6th MG: **LP_{13}+LP_{32}+LP_{51}** *[6 spatial modes]* **12×12 MIMO****

➔ ***Short impulse response after 90km***

➔ ***Performance degraded due to MG coupling (XT)***

*P. Sillard, OFC'16, Th1J.1
**S. Wittek et al., SUM'18, MF2.3

LOW-DMGD FMFs: *Mode Coupling*

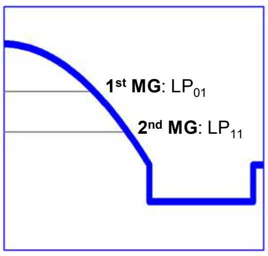
Decrease Δn_{eff} *and* maintain high $\Delta n_{eff\text{-}micro}$

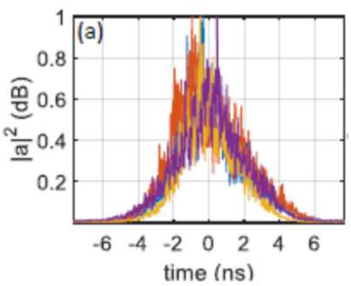
➔ ***Profile design is challenging***

➔ ***What else?***

Modes will ultimately Couple after 100s/1000s of km

Square-root behavior observed on a 1045km transmission over a DMGD-compensated link with 2 MGs*





*G. Rademacher et al., OFC'18, Th4C.4

OUTLINE

MDM and FMFs: *Impressive Progress*

Mode Division Multiplexing

➔ *S. Berdagué and P. Facq, Appl. Opt. (**1982**): 2 spatial modes over 10m*

➔ *A. Li at al.; M. Salsi et al.; R. Ryf et al. OFC (**2011**): 2 and 3 spatial modes over 10s of km*

- ***K. Shibahara et al., OFC (2018): 3 spatial modes over 6,300**km*
- ***R. Ryf et al., ECOC (2018): 45 spatial modes over 26.5**km*

Few-Mode Fibers

➔ *J. Sakai and T. Kimura, Opt. Lett. (**1977**): 3 spatial modes with DMGD <100ps/km*

➔ *A. Li at al.; M. Salsi et al.; R. Ryf et al. OFC (**2011**): 2- & 4-(LP)MG and 3-spatial-mode fibers*

- ***M. Bigot et al., NETWORKS (2017): 7-(LP)MG Fiber with XT ≤-24**dB/km*
- ***D. Molin et al., OFC (2018): 15-spatial-mode fiber with DMGD <80**ps/km*

DMGD Compensation

➔ *K. Morishita et al., IEEE Trans. on MTT (**1982**): "splicing the fibers with the opposite departures from the optimum index profile reduces the pulsewidth"*

➔ *T. Sakamoto et al., OFC (**2012**): 3-spatial-mode link with DMGD <5ps/km*

- ***P. Sillard et al., OFC (2017): 36-/45-spatial-mode link with DMGD <50**ps/km*

Strong Coupling

➔ *S.D. Personick, BSTJ (**1971**): "pulse spreading would grow as the square root of the length"*

- ***G. Rademacher et al., OFC (2018): square-root behavior** after 100s of km over 3-spatial-mode DMGD-compensated links*
- ***K. Shibahara et al., OFC (2019): square-root behavior** after 1,000s of km using cyclic mode permutation over 3-spatial-mode non-DMGD-compensated links*

MDM and FMFs: *Prospects*

WEAK COUPLING

- ➔ ***≥10-(LP)MG** [≥17-Spatial-Mode] **Fibers** with **XT** <**-35**dB/km*
- ➔ ***Short-Reach Transmissions** (~100s km)*
  - ➪ *MGDM over 100s of km with Direct Detection (no MIMO)*
  - ➪ *Real-Time Transmissions with Coherent Detection (2×2 and 4×4 MIMOs)*

MIMO

- ➔ *>**100-Spatial-Mode Fibers***
- ➔ ***FMFs** with **strong mode coupling***
- ➔ ***Long-Haul Transmissions** (~1000s km)*
  - ➪ *Square-root behavior with 10s of spatial modes over 1000s of km*
  - ➪ *Real-Time Transmissions with Coherent Detection (2N×2N MIMO)*

Thank you