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Fibers for mode multiplexing

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Outline

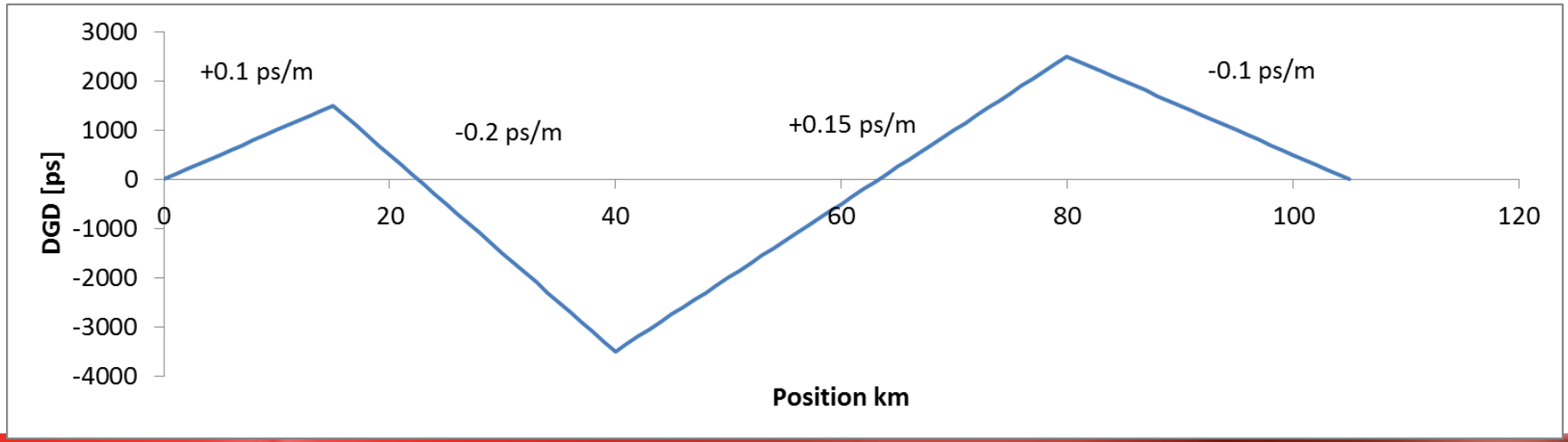
- **Requirements**
- **Examples made fibers**
- **Fiber characterization**

Requirements few mode fiber for mode division multiplexing

Property	Requirement	
Differential mode delay	Low	Systems with MIMO
	Not so important	Systems without MIMO
Mode coupling	Low to high	Systems with MIMO
	Low	Systems without MIMO
Splicing	Low splice loss Low cross coupling	
Attenuation	Low all modes	
Effective area	Large	
Dispersion	Large	

Requirements for Differential Mode Delay (DMD) of few mode fibers in MIMO based systems

- **DMD can be compensated by combining fibers with positive and negative DMD.**
- **Local accumulated DGD not too high**
  - ❖ To minimize width of plateau in impulse respond
    - ➢ *R. Ryf et al., ECOC,12, Tu.1.C.1*
- **Local DMD not too low**
  - ❖ to suppress intermodal nonlinearities
    - ➢ *R.-J. Essiambre et al., ECOC,12, Tu.1.C.4*



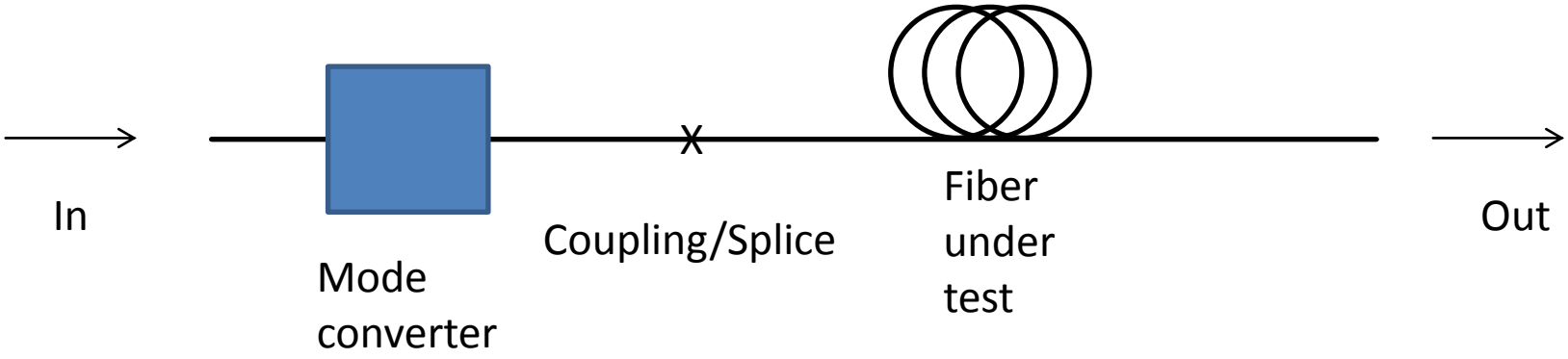
Fiber designs for few mode fibers

- **Step index fibers**
  - High DGD
- **Step index fibers with additional depressed cladding**
  - Low DGD possible for fibers supporting two LP modes
- **Graded index fibers**
  - Low DGD possible for few to many modes
  - Optional with a trench

Some selected reported results

Fiber design	No. of LP modes	DMD	Aeff	Atten.	Producer	Reference
		ps/m	μm^2	dB/km		
SI	4	+4.4 to +8.9	120 - 130	0.22	Prysmian	ECOC'11 Tu.5.LeCervin.7
Two layer SI	2	-0.4 and +0.4		< 0.30	NTT	OFC'12 OM2D.1
GI	2	~0	150-200	0.196	Fujikura	OE'13 pp. 16231
GI	2	-0.12 to +0.12	170-240		Corning	OECC'12 5C3-2
SI+Trench	2	+0.05	160	0.205	OFS	OFC'11 PDPB10
SI	2	2.3	160-210	0.186	OFS	OFC'12 OTh3I.4
GI+Trench	2	+0.2 to -0.2	95	0.195	OFS	OFC'12 PDP5A.1
SI	4	+2 to +4	210 – 310		OFS	OFC'12 OTh3I.4
GI+Trench	4	-0.3 to +0.3	90 - 180	~0.20	OFS	OFC'13, DP5.A.1

Characterization of Few Mode fiber

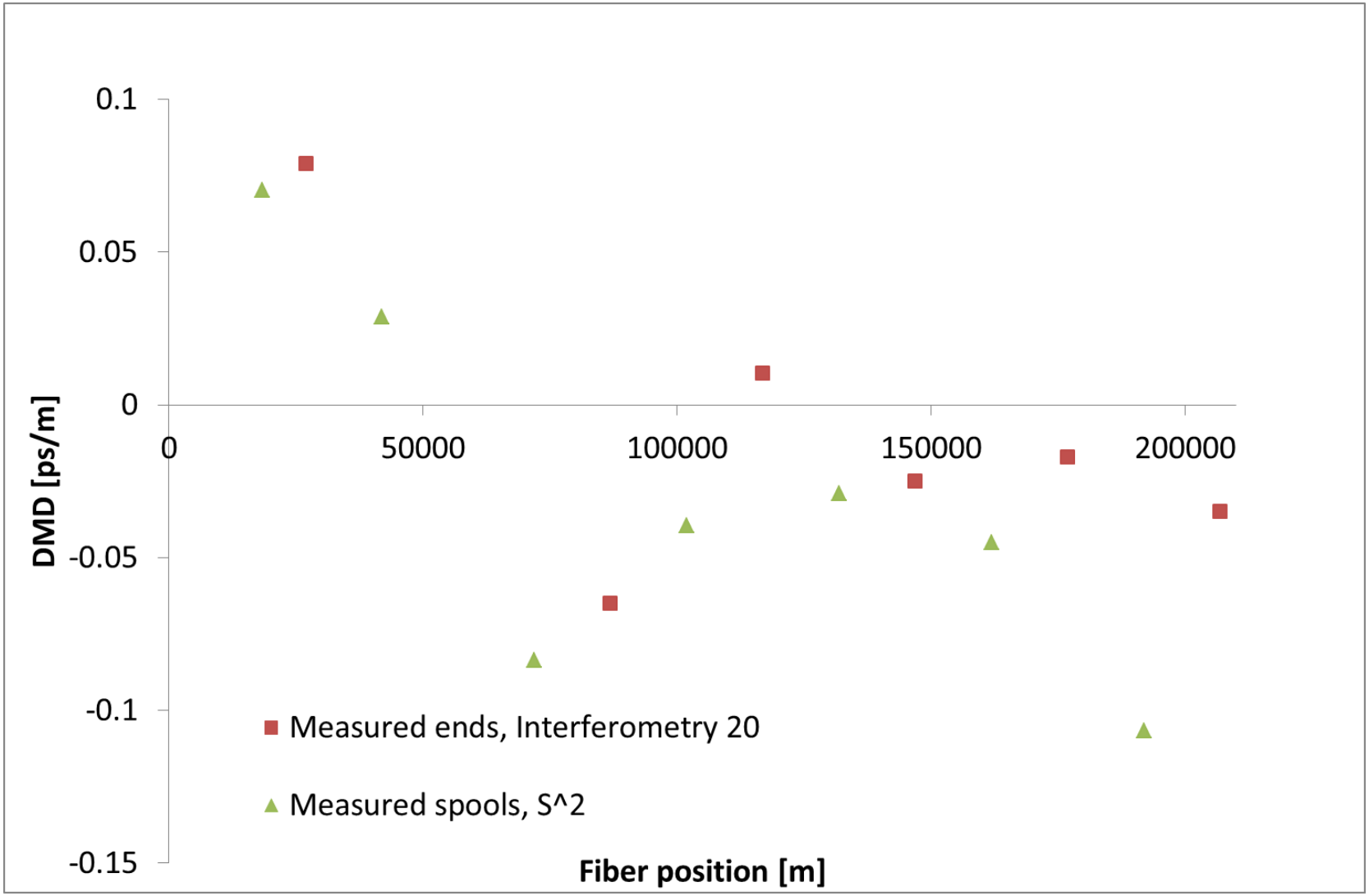


- **Mode converter and the coupling to the FUT should assure high extinction of the mode under test to other modes**
- **Coupling from the mode under test should be low to other modes in the length of fiber under test.**

Example properties OFS two mode fiber

Property	Unit	Simulations	Measured
DMD between LP_{11} and LP_{01}	ps/m		-0.1 to +0.1
Distributed Mode coupling			-20 dB/30 km
Dispersion LP_{01}	ps/(nm·km)	19.9	20.5
Dispersion slope LP_{01}	ps/(nm^2·km)	0.068	0.067
Effective area LP_{01}	μm^2	162	163
Dispersion LP_{11}	ps/(nm·km)	22.1	22.2
Dispersion slope LP_{11}	ps/(nm^2·km)	0.063	0.051
Effective area LP_{11}	μm^2	172	
Attenuation LP_{01}	dB/km		0.190
Attenuation LP_{11}	dB/km		0.194
PMD LP_{01}			0.03

Example, DMD variation along a fiber draw from a single preform



Conclusion

- **Few mode fibers supporting two or four LP modes (3 or 6 spatial modes) has been fabricated by several groups and successfully use for transmission**
- **Still possible to optimize properties**
- **Still work to do to scale up number of modes**
- **New requirements for characterization**
  - ❖ Area for future standardization work

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